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NONLINEAR ANALYSIS OF A TM-46
SOVIET LAND MINE



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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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A static and dynamic analysis of a TM-46 land mine is presented.

The objective of this study was to establish a finite element analysis of the mine including an accurate modeling of the contact conditions.

The report presents the finite element modeling and solution results for the static buckling response and the dynamic response under blast pressure loading.

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## 1. INTRODUCTION

In some previous work Gupta et al analyzed a mine casing for its nonlinear response [1,2]. The structure is described in detail in ref. [2]. This description gives the geometry and material data and the assumed loading on the structure.

Figures 1 to 5 show the data pertaining to the analysis of the mine. Figure 1 shows a cross-section of the (almost) axisymmetric structure. The casing consists of steel, the secondary booster fuzewell explosive is the tetryl material and the central cavity in the main body is filled with the TNT explosive powder. Figure 2 gives a perspective view of the mine and indicates how the steel material properties have been determined from measurements on tensile specimens. Some test results to determine the uniaxial stress-strain response of the steel are given in Fig. 3. Gupta used these test results to determine a bilinear approximation and a multilinear approximation has been used for his analysis. Figure 4 gives the material relationship used to describe the filler material, as established in ref. [2]. Finally, Fig. 5 shows the loading on the top plate of the mine.

The material relationships for the TNT and filler material are also given in Table 1.

In their study, Gupta et al established a finite element discretization of the mine and solved for the geometric and material nonlinear response. A major difficulty in their study was to model the contact that is established between the top plate of the mine and the cover plate of the filler material. Since the deformations of the top plate are very large and contact is established over practically the whole cover plate at an early time of the response, the modeling of the contact conditions is an important ingredient of the analysis process.

The reason that Gupta et al had difficulty modeling the contact conditions accurately was that the ADINA program at the time of study did not offer an automatic contact algorithm.

The objective of the present study was to establish a finite element analysis including a more accurate modeling of the contact conditions. In this study ADINA 84 was used with some improvements, as described below (versus the use of ADINA 81 by Gupta et al).

The report is presenting the following information. In the next section the finite element model is described with special emphasis on the element selection and the boundary conditions used. In Section 3 the solution results are then given, as obtained in a static analysis and a dynamic analysis. These results are discussed and interpreted in Section 4. The discussion includes a description of the difficulties encountered in the analysis. Finally, in the last section, the major results are summarized and recommendations for further work on the problem are given.

## 2. THE FINITE ELEMENT MODEL

The finite element model used for the analysis is shown in Fig. 6.

- Eight-node elements were used to model the main cylindrical steel body and the top cover and stepped section.

- Five and four-node elements were used to model the TNT explosive and Tetryl explosive materials in the mine.

This model was used for the static analysis. For the dynamic solution it was found that the stepped part of the top plate was more appropriately modeled using 4-node elements. As a result, two 4-node elements were used to replace one 8-node element used in static analysis, see Fig. 12.

Since an axisymmetric structure is considered, only half of the mine was discretized. This model was assumed to be supported by a rigid foundation.

The stress-strain relationships used for the materials are given in Figs. 3 and 4.

The contact conditions between the top plate and the cover plate were modeled using the contact algorithm of ADINA 84 [3]. However, since the automatic load stepping for solution of response had to be used for the static analysis, a modification to the standard algorithm was necessary. This modification now allows the solution of the equations

$$\begin{bmatrix} {}^{t+\Delta t}\underline{K}^{(i-1)} & \underline{K}_\lambda \\ \underline{K}_\lambda^T & \underline{0} \end{bmatrix} \begin{bmatrix} \Delta\underline{U}^{(i)} \\ \Delta\underline{\lambda}^{(i)} \end{bmatrix} = \begin{bmatrix} {}^{t+\Delta t}\mu^{(i-1)}\underline{R} \\ \underline{0} \end{bmatrix} - \begin{bmatrix} {}^{t+\Delta t}\underline{F}^{(i-1)} \\ \underline{0} \end{bmatrix} + \begin{bmatrix} {}^{t+\Delta t}\underline{R}_c^{(i-1)} \\ \underline{0} \end{bmatrix} \qquad (1)$$

where

$^{t+\Delta t}\underline{K}^{(i-1)}$ = tangent stiffness matrix

$\underline{K}_\lambda$ = contact constraint matrix

$\underline{R}$ = externally applied load vector, corresponding to a uniform pressure on the top cover plate of the mine

$^{t+\Delta t}\mu^{(i-1)}$ = load factor, scaling the load vector to trace out the load-displacement response [4]

$^{t+\Delta t}\underline{F}^{(i-1)}$ = nodal point forces corresponding to the internal element stresses

$^{t+\Delta t}\underline{R}_c^{(i-1)}$ = contact forces

$\Delta\underline{U}^{(i)}$ = incremental displacement

$\Delta\underline{\lambda}^{(i)}$ = vector of Lagrange multipliers

The left superscript $t+\Delta t$ denotes time at $t+\Delta t$ and the iteration counter is (i).

The modifications necessary in ADINA 84 pertain to the use of the automatic load stepping with the load factor $^{t+\Delta t}\mu^{(i-1)}$ in Eq. (1), together with the contact conditions. Here the algorithm of ref. [4] was extended to include the contact conditions as a constraint.

The solution results in Section 3 show that the automatic load stepping scheme had to be used because of the successive collapse (limit) points reached due to the physical collapse of the stepped section of the top plate. Since the automatic load stepping scheme was used in the static analysis, it had to be assumed that the load was deformation independent.

In the dynamic analysis the standard incremental equations of motion were solved, with the applied blast pressure shown in Fig. 5.

The finite element large deformation, large strain formulation used for the steel casing sections was the U.L.H. (updated Lagrangian Hencky) formulation described in refs. [5,6]. For the TNT explosive material and the fuze-well filler material the materially-nonlinear-only formulation was used, since relatively small deformations were anticipated in this part of the mine.

## 3. SOLUTION RESULTS

The static and dynamic solution results are presented in Figs. 7 to 29.

a. Static Analysis of the Mine

The static solution results of the mine are given in Fig. 7 as a pressure-displacement response. As can be seen from the figure a successive collapse behavior of the stepped section of the top plate is observed and at a pressure of 0.16 N/mm$^2$, the stepped part of the top cover can be considered as destroyed.

Figures 8, 9 and 10 give some overall deformations of the mine at different load levels corresponding to points (1), (2) and (3) in Fig. 6 (point (1) - first contact, point (2) - center top plate comes into contact with the main body, point (3) - final deformations of the top part). As these figures show, the main body of the mine is very stiff. Note that Fig. 11 gives the response solution for a very high (perhaps impractical) pressure of 500 N/mm$^2$.

b. Dynamic Analysis of the Mine

A nonlinear dynamic analysis has been performed to find the response of the mine for the blast loading using the U.L.H. formulation.

In order to ascertain that the model has been formulated correctly, an eigenfreqency and mode shape analysis was performed first as in Fig. 12. The frequencies and corresponding periods are given in Table 2.

Table 2

| Frequency (cps) | Period (sec) |
|---|---|
| $0.1147 \cdot 10^4$ | $0.8718 \cdot 10^{-3}$ |
| $0.4799 \cdot 10^4$ | $0.2084 \cdot 10^{-3}$ |
| $0.8146 \cdot 10^4$ | $0.1228 \cdot 10^{-3}$ |
| $0.1512 \cdot 10^5$ | $0.6612 \cdot 10^{-4}$ |

It is noted that these predicted frequencies (cycles per sec) are considerably lower than the values reported by Gupta et al [27]. The difference is deemed due to the fact that Gupta et al used a stiffer mesh and used springs to model the contact between the top and cover plates.

This conclusion is substantiated by an approximate analysis in which it is assumed that the top plate acts as a single degree of freedom system.

Calculating the lowest frequency of a mesh close to Gupta's mesh (but not including the springs) gives

$$\left(\omega_1^{GM}\right)^2 = 6.7 \cdot 10^7 \text{ rad/sec}$$

whereas Gupta reports [2]

$$\left(\omega_1^{G}\right)^2 = 3.65 \cdot 10^8 \text{ rad/sec}$$

However, for a single degree of freedom system, we have

$$\omega_1^2 = \frac{K}{M}$$

$$\tilde{\omega}_2^2 = \frac{K + K_s}{M}$$

We now let K be the stiffness of the cover plate, M the corresponding mass and $K_s$ be the stiffness due to the applied springs. The stiffness K can be evaluated from the static response (Fig. 7):

$$K = \frac{N}{\Delta L} = \frac{p \cdot A}{\Delta L} = \frac{0.09 \cdot \pi \cdot 100^2}{2.0} = 1414 \text{ [N/mm]}$$

Having obtained K, we can calculate the corresponding mass:

$$M = \frac{1414}{6.7 \cdot 10^7} = 2.1 \cdot 10^{-5},$$

The stiffness of the springs can be evaluated as:

$$K_s = \frac{E_s A}{L} = \left( \frac{\pi(100^2 - 40^2)}{25.0} + \frac{\pi(150^2 - 100^2)}{12} \right) 1.4 = 6060 \text{ [N/mm]}$$

where the Young's modulus for the springs has been obtained from Fig. 8, reference [2]

$$E_s = \frac{100}{0.5} = 200 \text{ psi} = 1.4 \text{ N/mm}^2$$

Hence

$$\tilde{\omega}_2^2 = \frac{1414 + 6060}{2.1 \cdot 10^{-5}} = 3.56 \cdot 10^8$$

As can be seen the calculated value for $\tilde{\omega}_2^2$ is close to the value obtained by Gupta et al [2].

For the nonlinear dynamic analysis, the mesh in Fig. 12 was used. Figures 13 to 29 show the calculated nonlinear dynamic response of the mine. The response was obtained using the trapezoidal implicit time integration scheme. The figures show large deformations in the stepped section of the top plate, and that these deformations occur in a different manner than in the static analysis.

The analysis was conducted with the time steps varying between 0.1E-07 and and 0.1E-05 sec. and a total of 2050 time steps with full Newton equilibrium iterations in each step was used to obtain the solution up to 0.102E-03 sec. (0.102 ms), as in Fig.30. At this point the top plate is considered to be destroyed and the main body of the mine gives a very stiff further response.

## 4. DISCUSSION

Several difficulties were encountered in the static analysis of the mine. The stepped part is a thin-walled structure connected to a relatively thick central plate and massive solid main body. As a result, the plate responds in a multi-buckling behavior which together with contact conditions and very large deformations creates solution difficulties.

The large deformations of the mine occur mainly in the area of the top cover plate, and a relatively low pressure is only needed to destroy the upper part of the mine. The stepped part was subjected to forty percent strain at a pressure $p = 0.16$ N/mm$^2$ and at the pressure $p = 16$ N/mm$^2$ the top central plate is in full contact with the main body. The main body which is supported on a rigid roller, did not show significant deformations at this pressure. However, as the load was increased (up to an artificially large value of 500 N/mm$^2$), the deformation in the main body increased significantly, as can be seen in Fig. 11.

As for the dynamic response prediction, the implicit trapezoidal rule time integration scheme with the full Newton method was used. The response of the system is shown in Figs. 13-29. The flexible stepped part is subjected again to very large deformations and large strains (see Fig. 21), which causes numerical difficulties due to dynamic buckling behavior and contact. In order to obtain convergence in the iterations a sufficiently small time step had to be used and the time step size was varied between $10^{-2}$ μsec and 1 μsec.

The failure in some elements in the stepped part has been observed at a relatively early time beginning with time t = 0.00003 sec (0.03 ms). In order to continue the computation, (since damage of the stepped part does not mean that the whole mine is deactivated) very large strains were allowed in the response.

The progressive behavior of the top cover can be seen in Figs. 13 - 29. At time t = 0.0001 sec, (0.1 ms) the top part of the mine was severely distorted and the analysis could not be carried further. However, again no significant deformations are found in the main body, which did not show any evidence of failure at this stage.

These observations are in good agreement with the observations given by Gupta et al [2]. The highest strains in the main body were observed near the corners and in the contact areas between the top plate and the cover plate of the mine casing.

## 5. CONCLUSIONS AND RECOMMENDATIONS

In the present analysis the mine was supported on rigid rollers. It should be noted that the mine on an elastic foundation might display a different response in some respects from that presented in this work. However, the underlying analysis difficulties and major response can be expected to remain the same and some suggestions can be summarized.

The analysis is difficult to conduct because of the large deformations and highly inelastic response of the mine. In the study the response of the mine was obtained for very large pressures and a complex collapse response of the top plate was observed, but the main body underwent relatively small deformations.

The modeling and analysis of the mine could be improved by the following features:

- For the analysis it would be most effective to employ axisymmetric thin shell elements instead of the axisymmetric solid elements. Such elements should be available in ADINA for this type of analysis.

  The major reason is that solid elements becoming too thin as required in this analysis develop spurious stresses through the thickness of the elements, which in time renders the contact solution difficult.

- Failure criteria should be used in the model that realistically removes elements during the response history. However, such elements removed will render the analysis (in particular the static solution) more difficult because of the abrupt change in system properties. In the reported analysis, elements were removed using the element birth and death option.

- The dynamic analysis might be considerably easier if an effective automatic time step selection were available in ADINA. We anticipate that in the next release of ADINA such scheme will be available.

The complete analysis was conducted on a MicroVAX computer: this was effective to construct the model and perform the runs as reported in this document. However, as a next step it would be effective to perform any further analysis on a large frame computer. In this case the computer processing times for a run would be measured in minutes rather than in hours (as for the MicroVAX) and parametric studies are possible.

Table 1. ADINA Input Values for Bulk and Shear Moduli for Filler Materials.

TNT EXPLOSIVE

| Point No. | $\varepsilon_V$ (%) | $K_\ell$ (GPa) | $K_U$ (GPa) | $G_\ell$ (GPa) |
|---|---|---|---|---|
| 1 | 0 | 21.72 | 21.72 | 10.62 |
| 2 | 1.0 | 23.03 | 23.03 | 11.24 |
| 3 | 3.0 | 25.65 | 25.65 | 12.55 |
| 4 | 5.0 | 28.68 | 28.68 | 14.01 |
| 5 | 9.0 | 35.85 | 35.85 | 17.51 |
| 6 | 11.0 | 40.20 | 40.20 | 19.65 |

TETRYL

| Point No. | $\varepsilon_V$ (%) | $K_\ell$ (GPa) | $K_U$ (GPa) | $G_\ell$ (GPa) |
|---|---|---|---|---|
| 1 | 0 | 10.5 | 10.5 | 4.03 |
| 2 | 1.0 | 11.15 | 11.15 | 4.27 |
| 3 | 3.0 | 12.59 | 12.59 | 4.83 |
| 4 | 5.0 | 14.24 | 14.24 | 5.46 |
| 5 | 8.0 | 17.2 | 17.2 | 6.60 |
| 6 | 10.0 | 19.56 | 19.56 | 7.50 |

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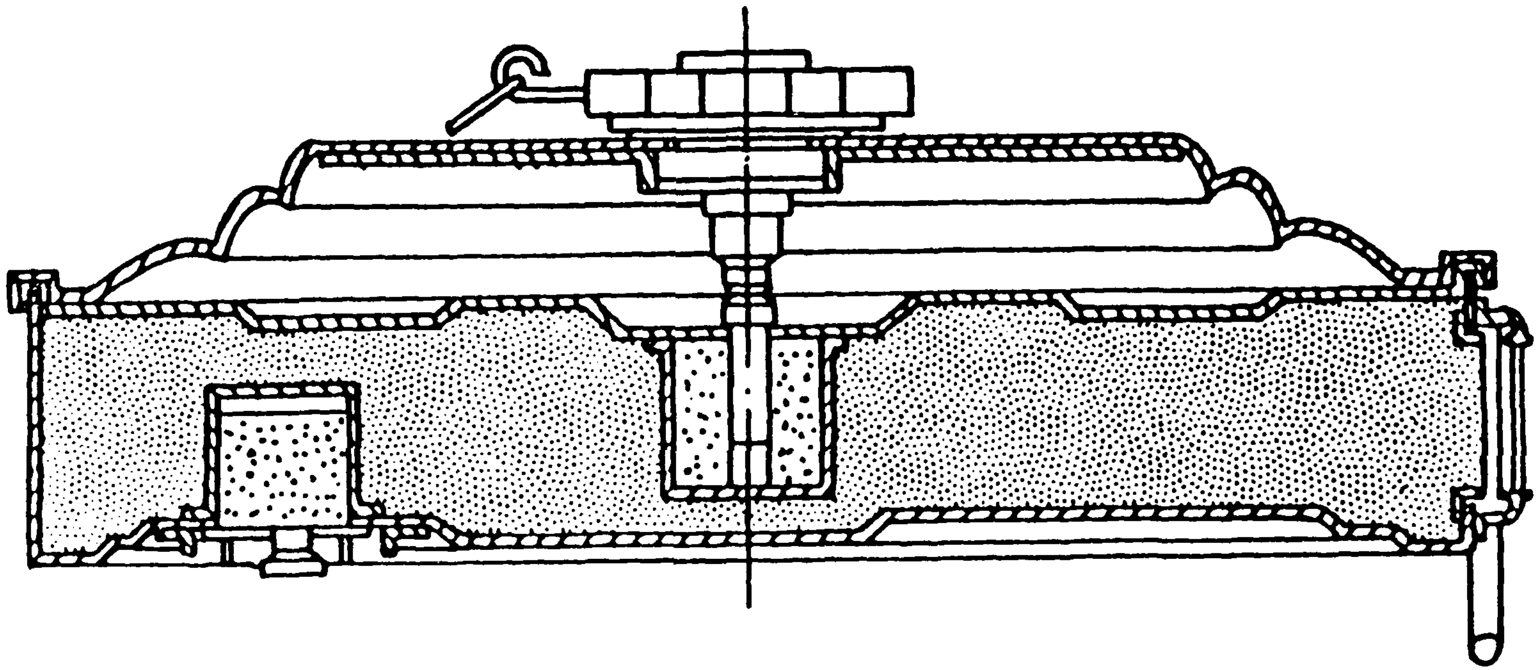

Fig. 1  Cross-section of mine

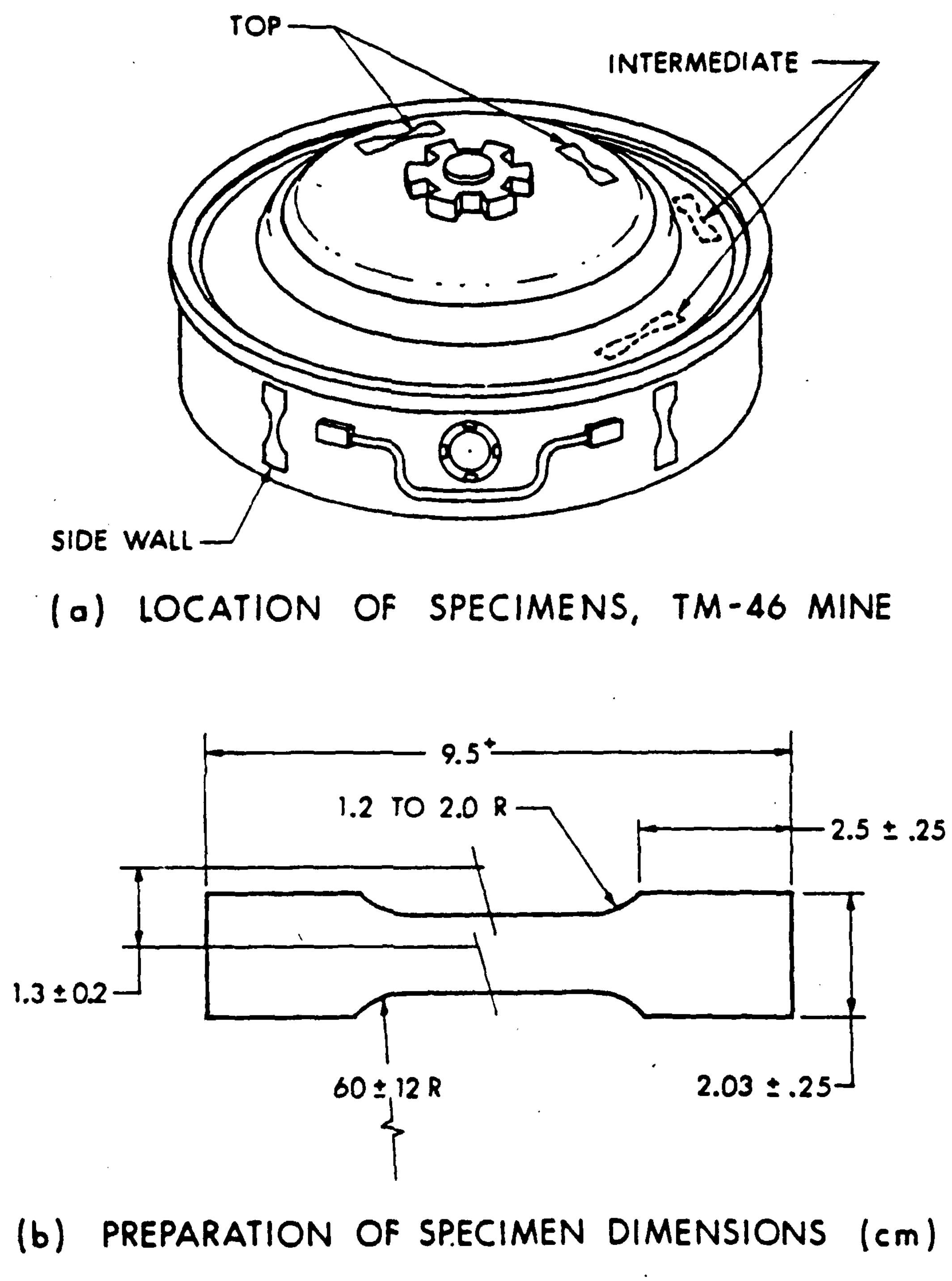


Fig. 2 Perspective view of mine structure

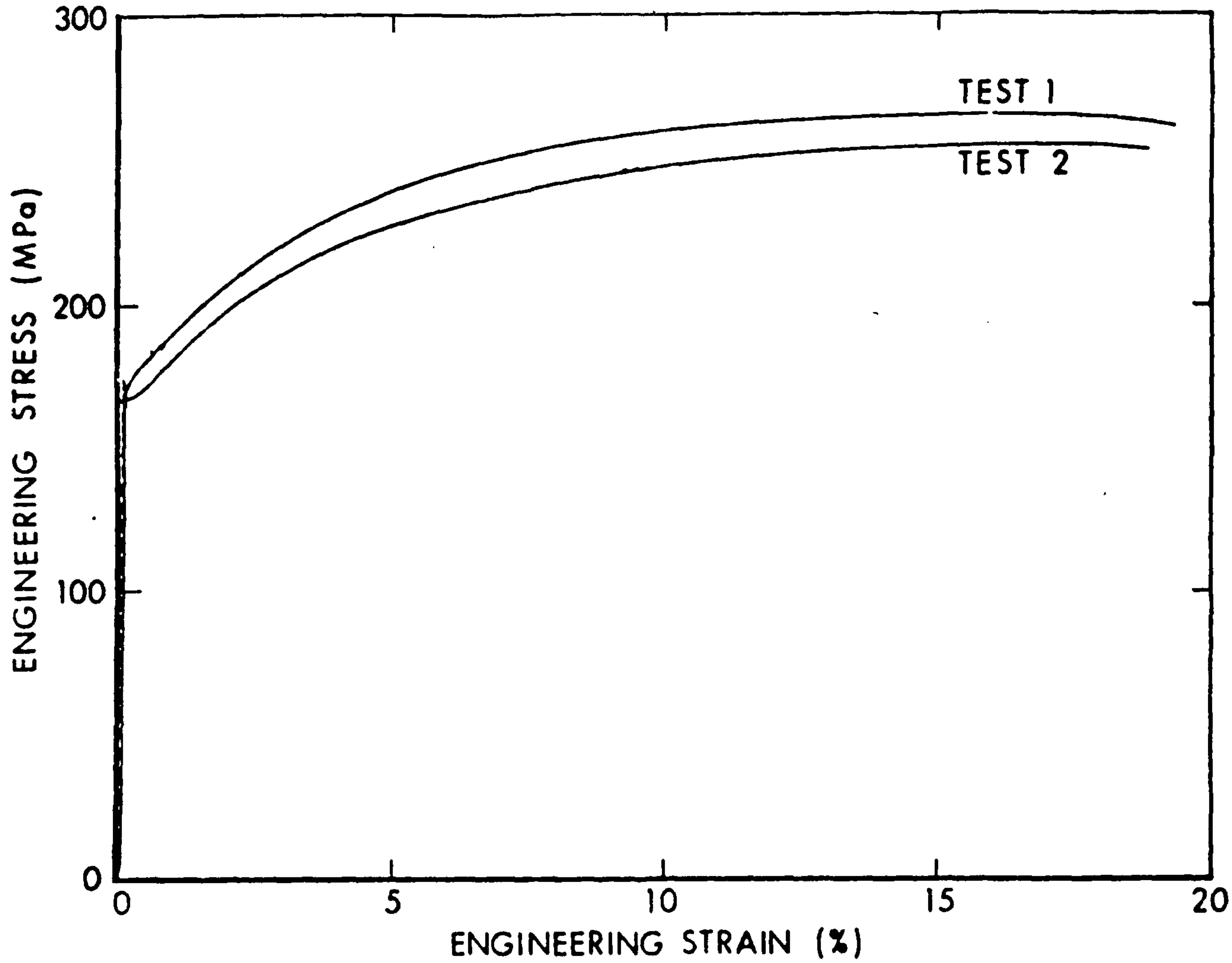


Fig. 3 Material elastic-plastic uniaxial test response

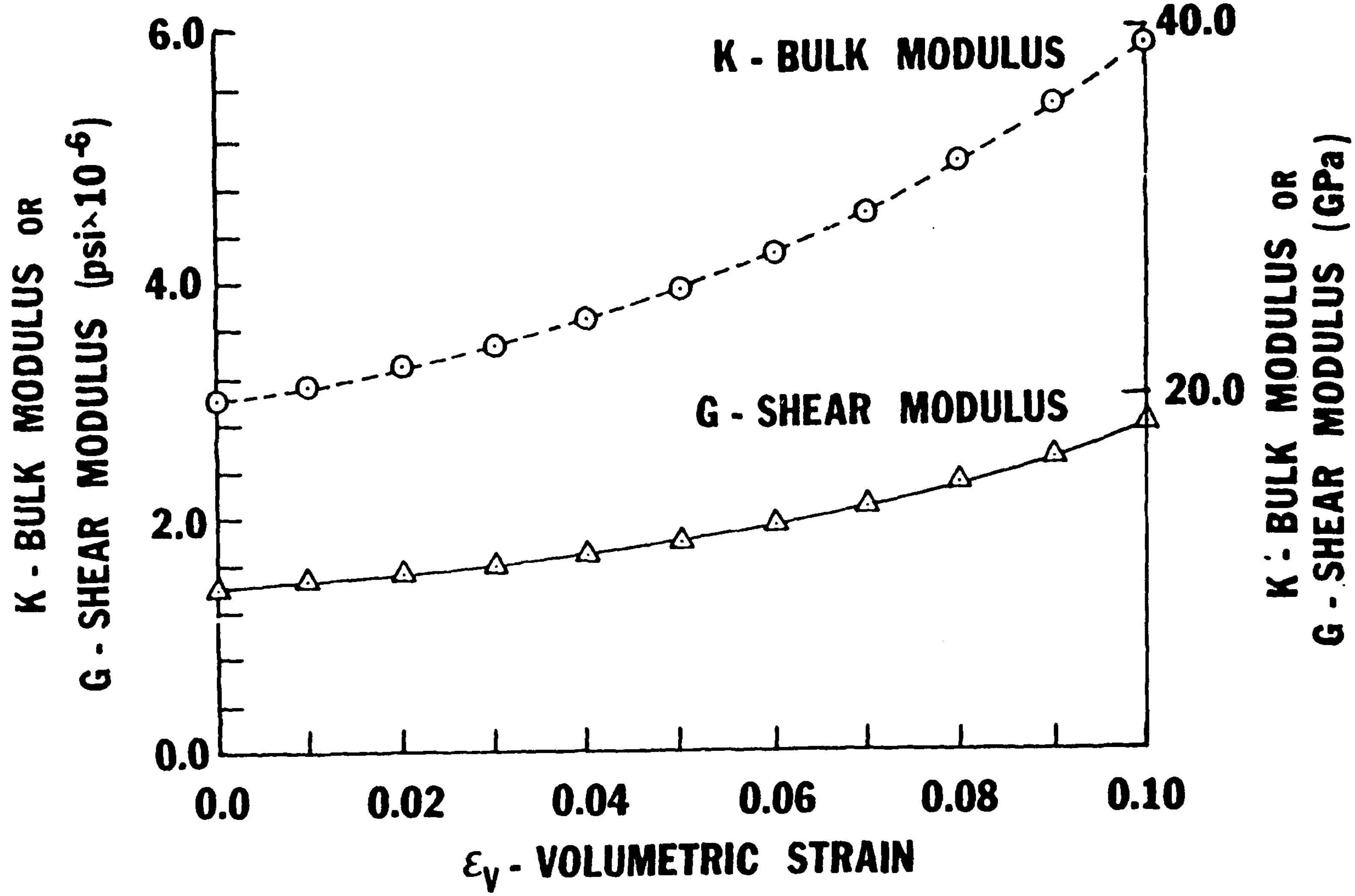


Fig. 4 Material for the TNT Explosive

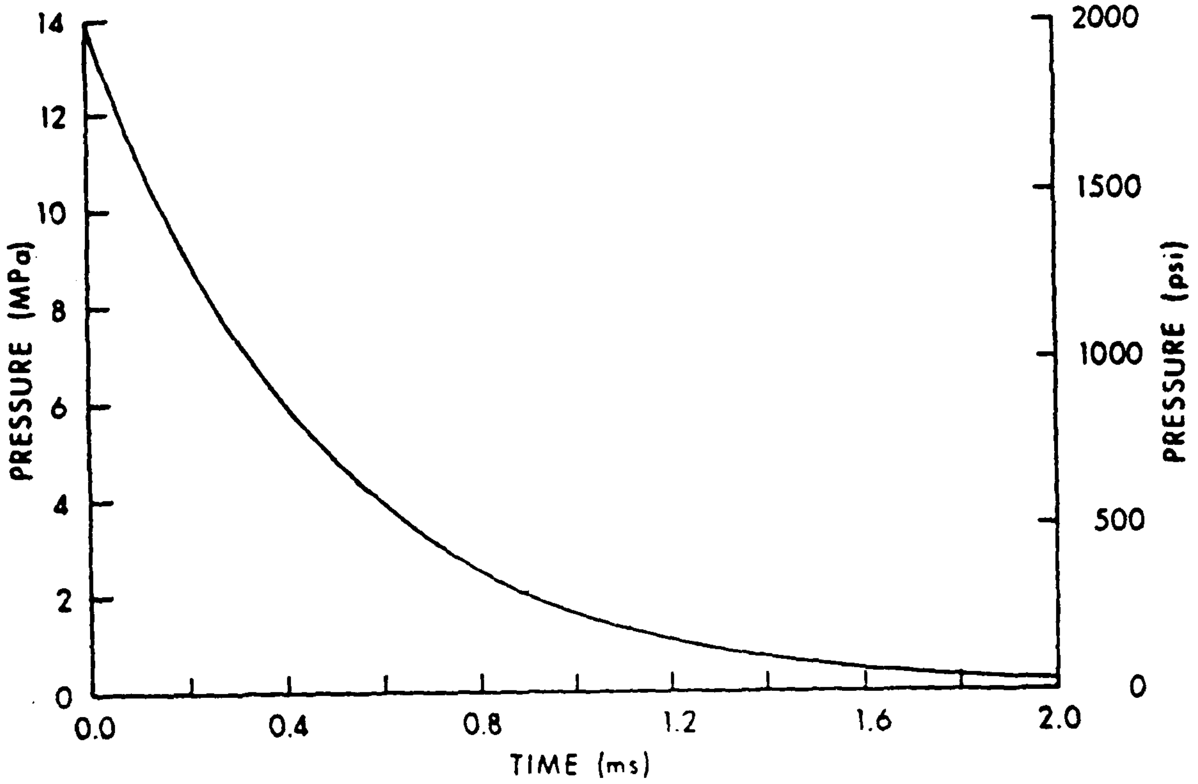


Fig. 5 Loading applied to top plate of mine

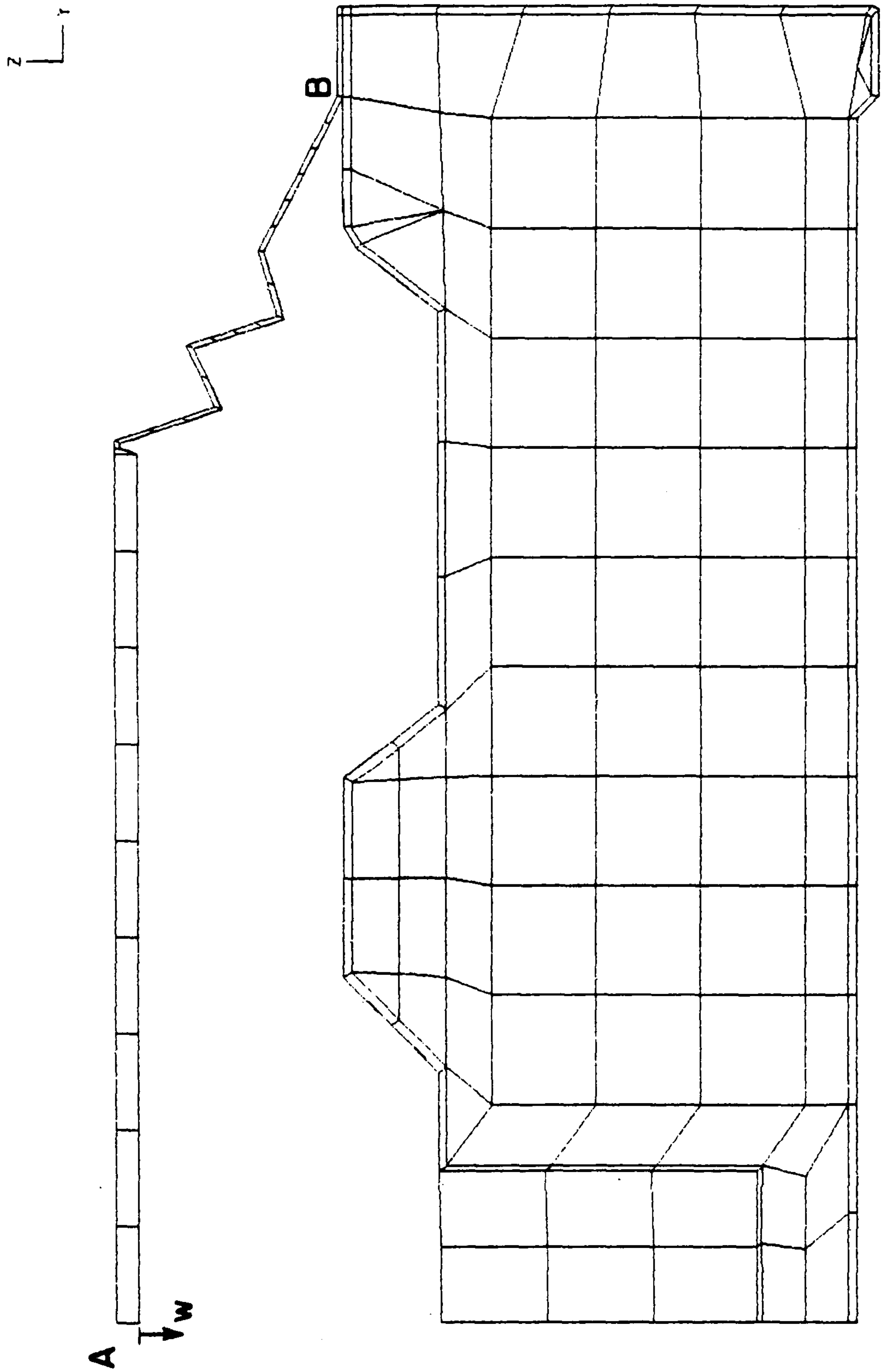


Fig. 6 Finite element mesh used in static analysis

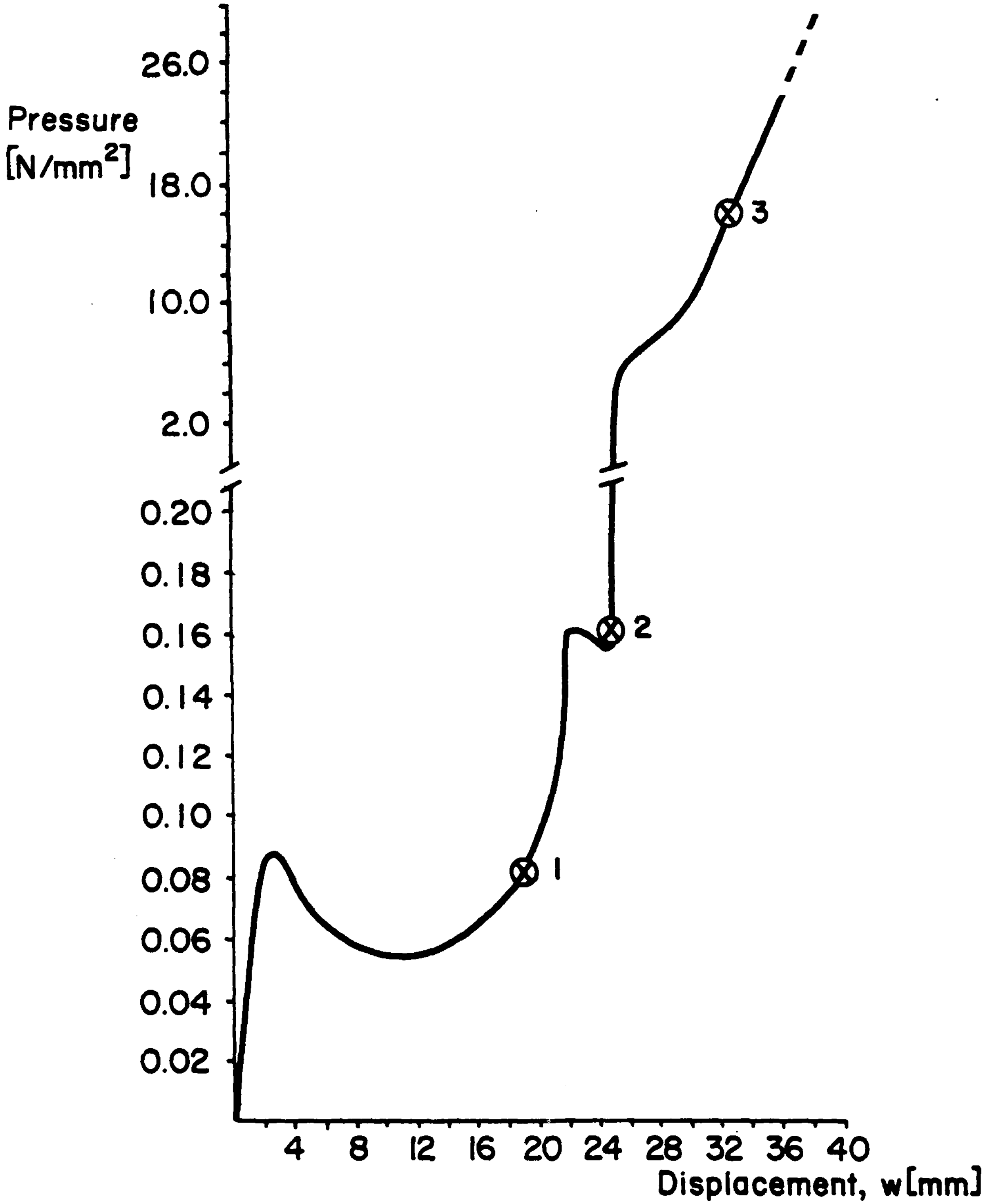


Fig. 7 Load displacement response of top plate of mine

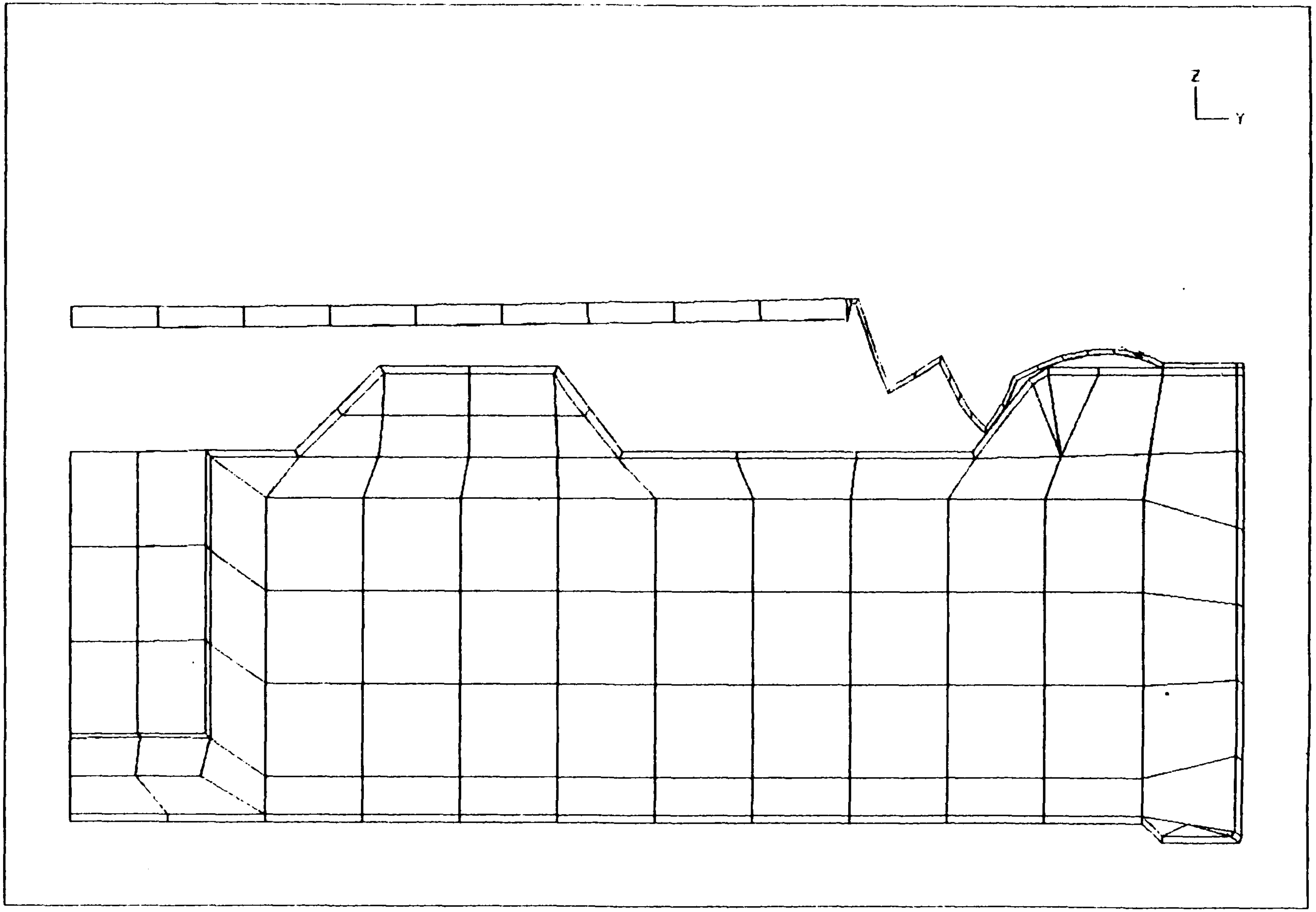


Fig. 8 Deformation of mine at load level corresponding to point 1 in Fig. 7, $p = 0.08\ N/mm^2$

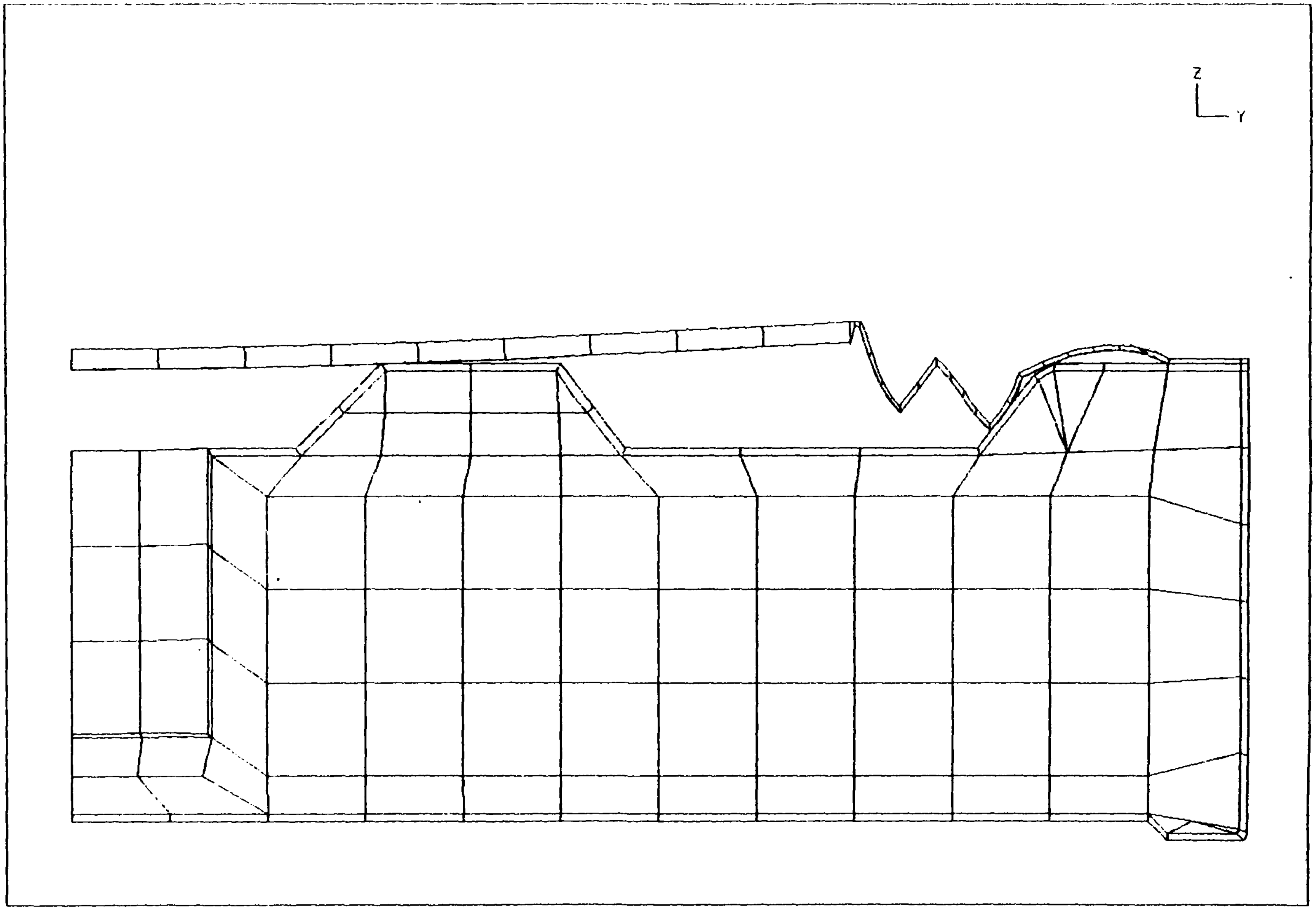


Fig. 9 Deformation of mine at load level corresponding to point 2 in Fig. 7, $p = 0.16\ N/mm^2$

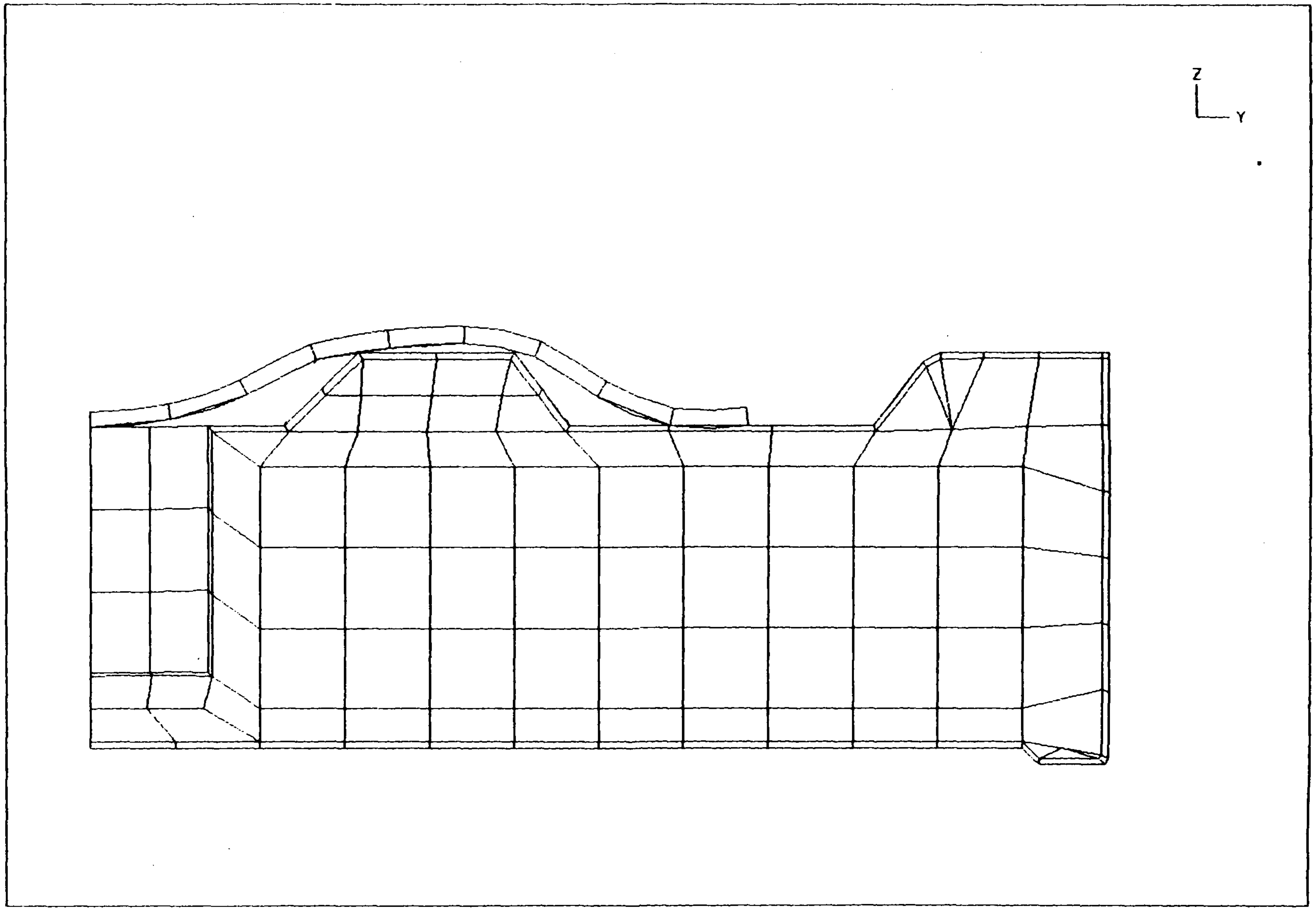


Fig. 10 Deformation of mine at load level corresponding to point 3 in Fig. 7 at load level $p = 16\ N/mm^2$

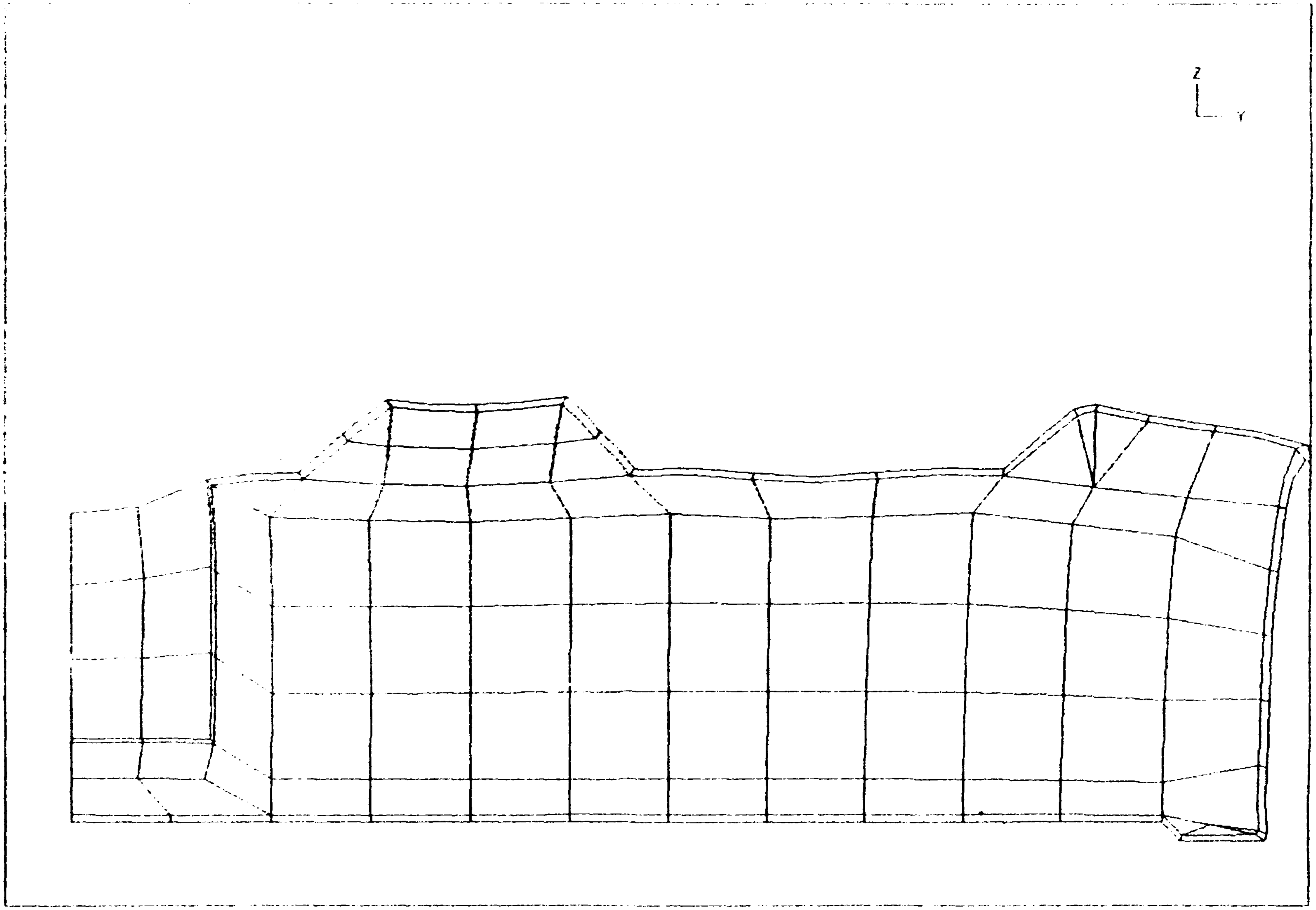


Fig. 11  Main body of mine at load level p = 500 N/mm$^2$

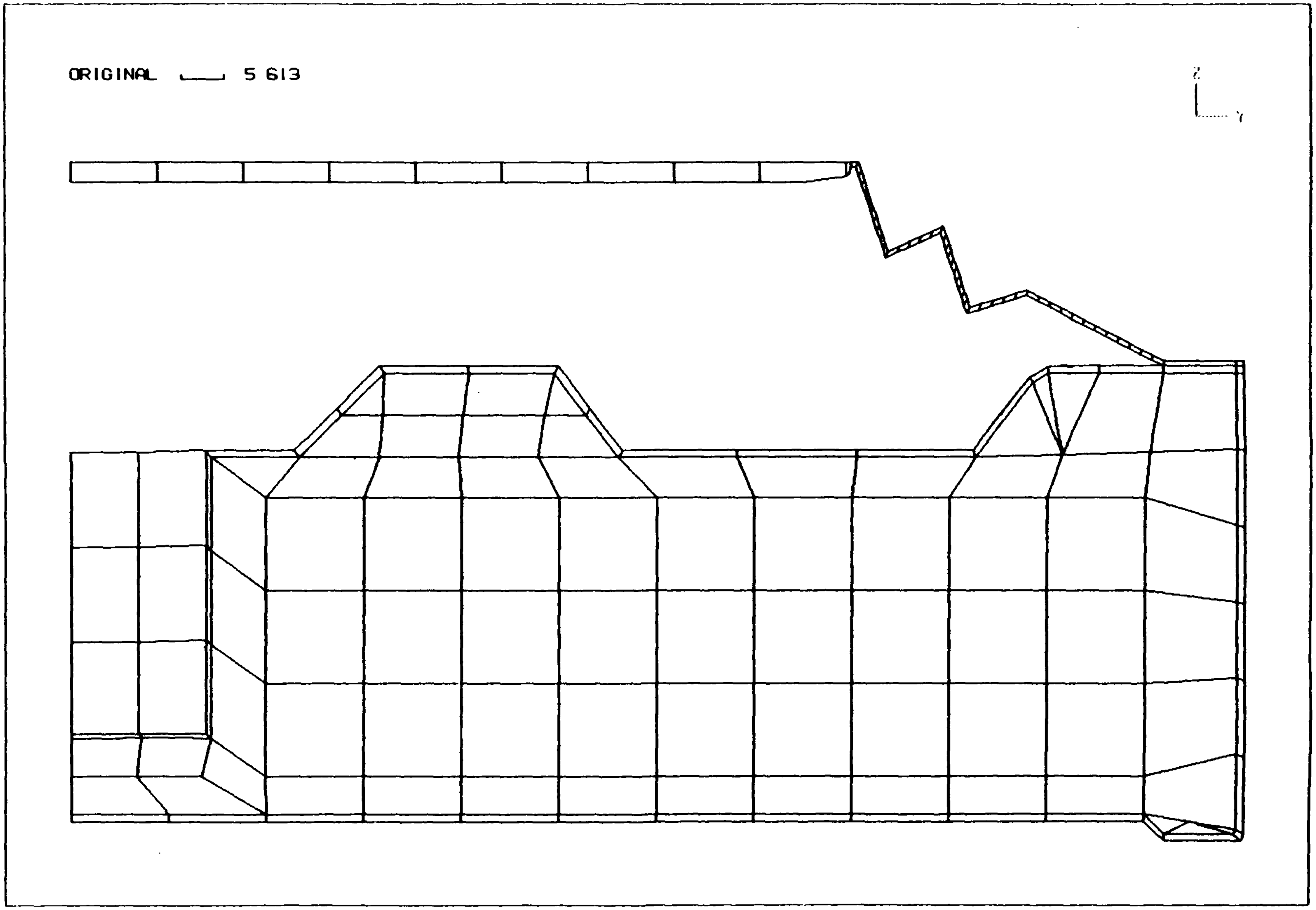


Fig. 12 Finite element mesh used in dynamic analysis, 4-node elements in the stepped region

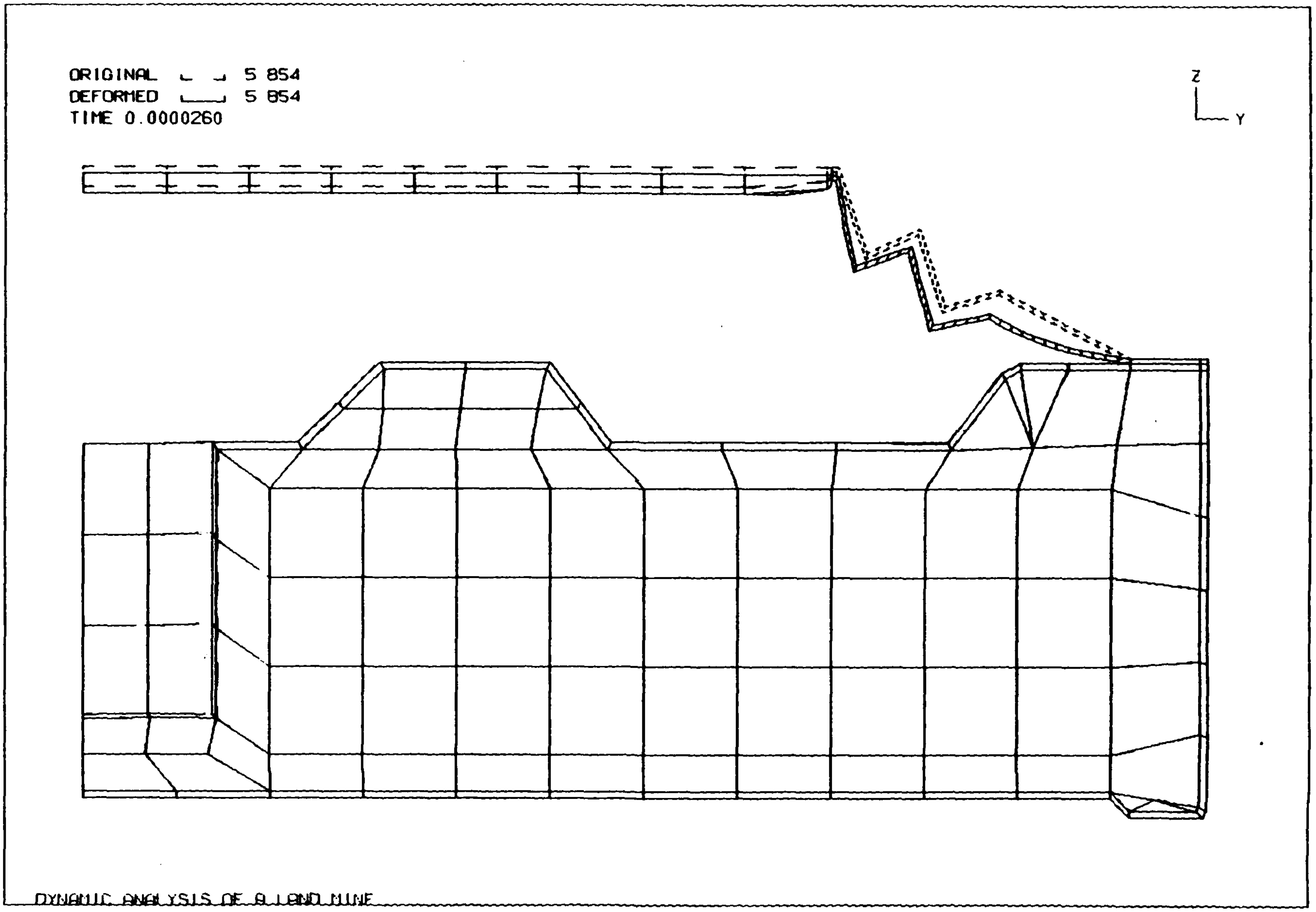


Fig. 13 Deformation of mine at t = 0.026 ms

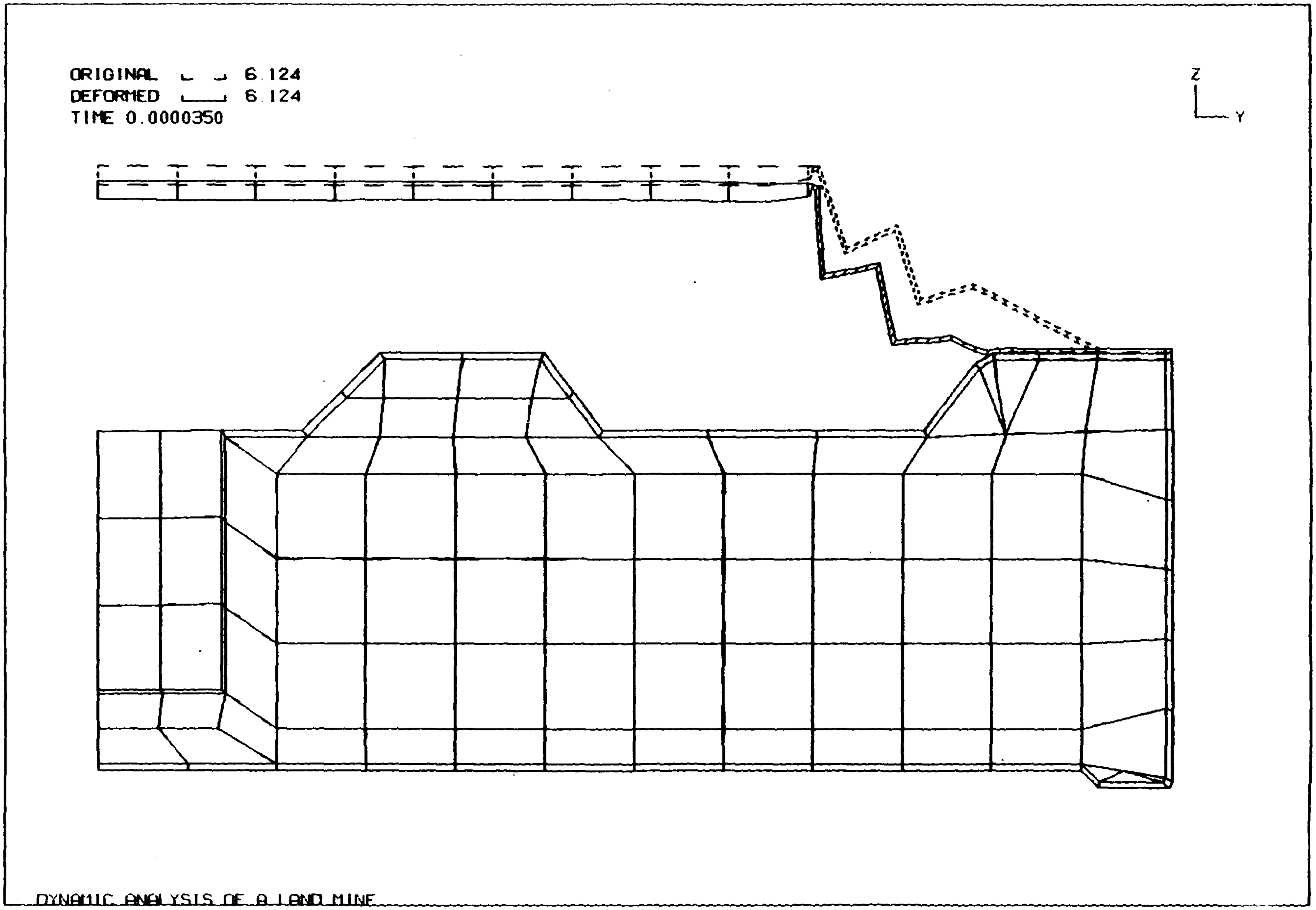


Fig. 14 Deformation of mine at time t = 0.035 ms

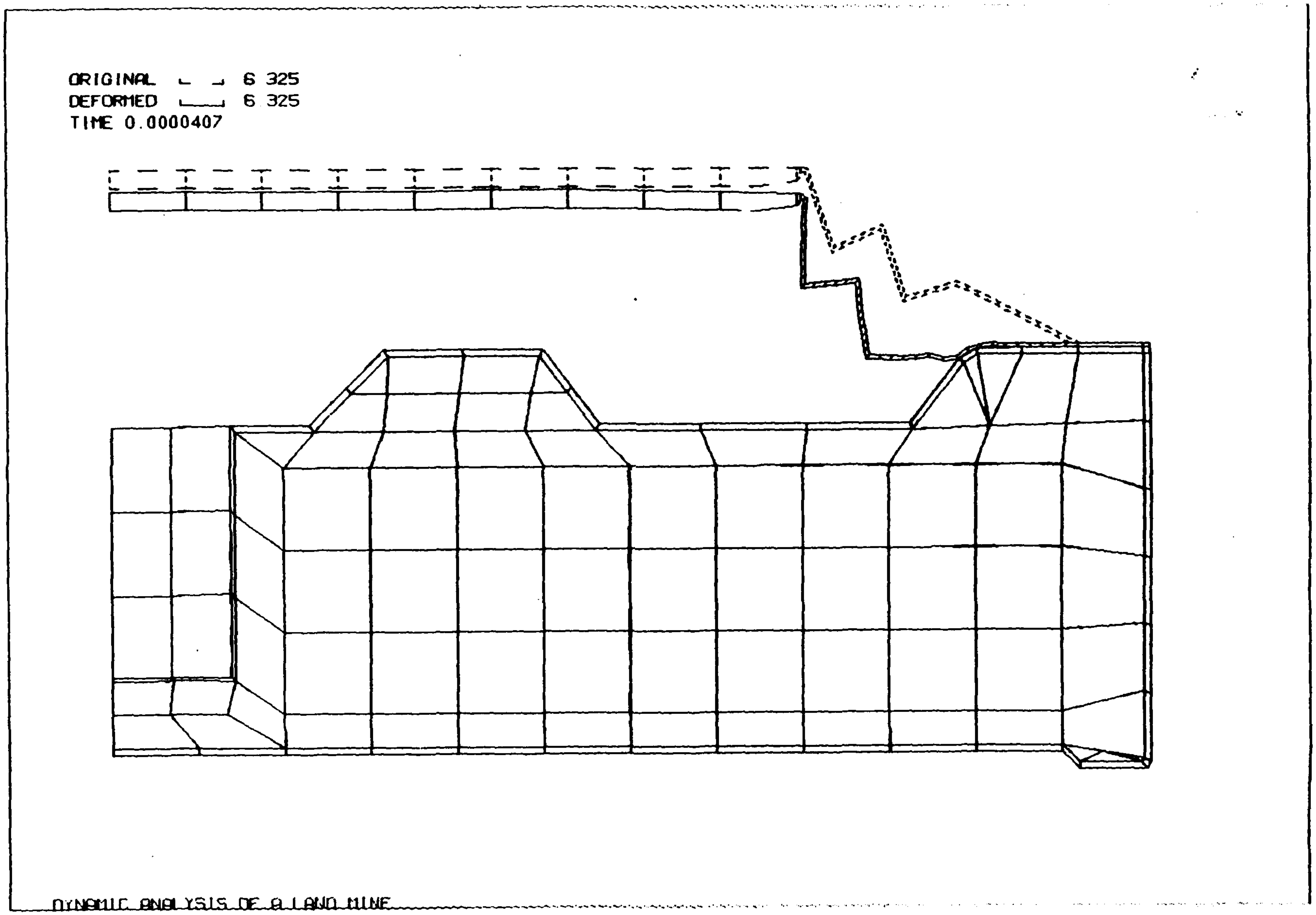


Fig. 15  Deformation of mine at time t = 0.0407 ms

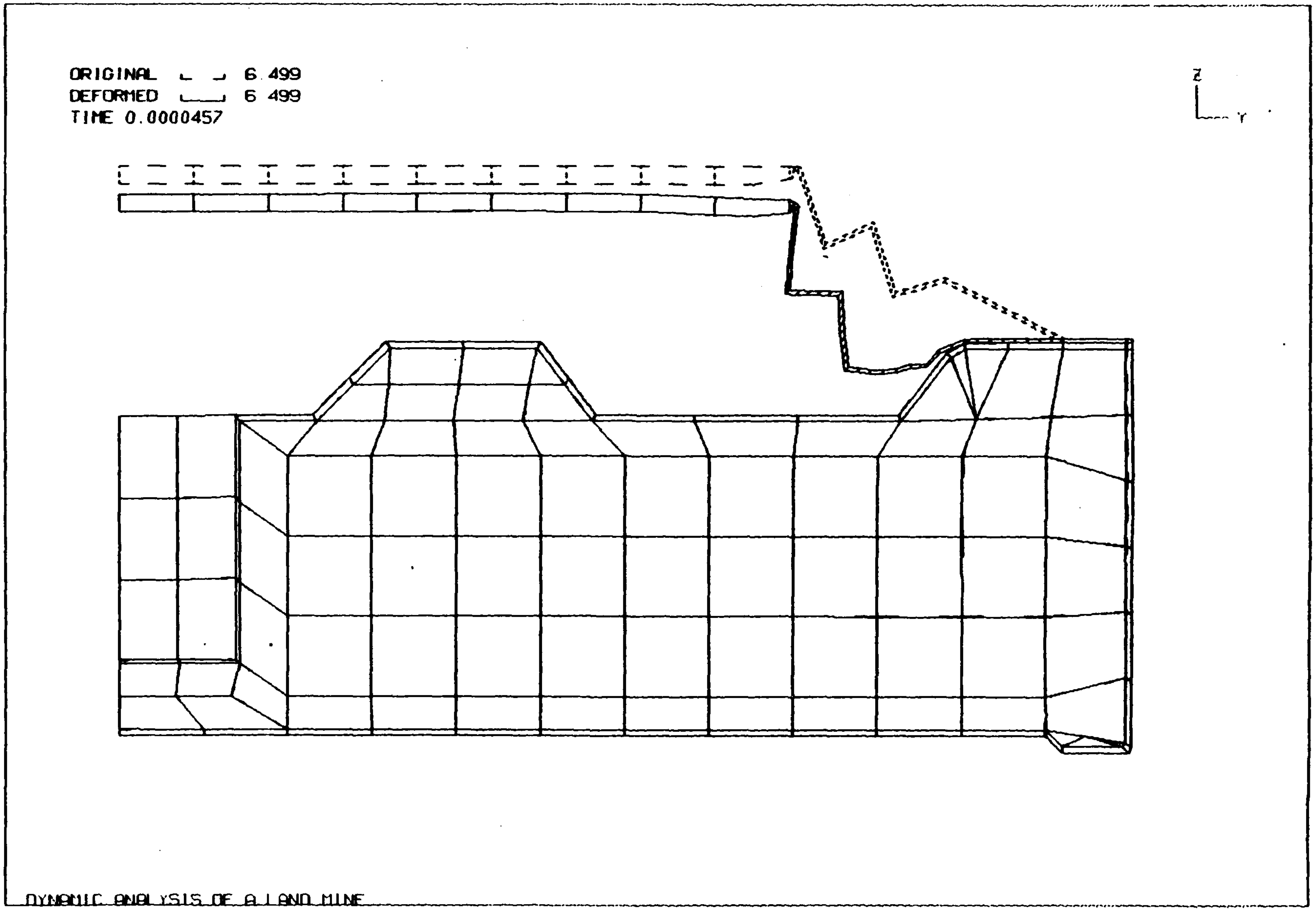


Fig. 16 Deformation of mine at time t = 0.0457 ms

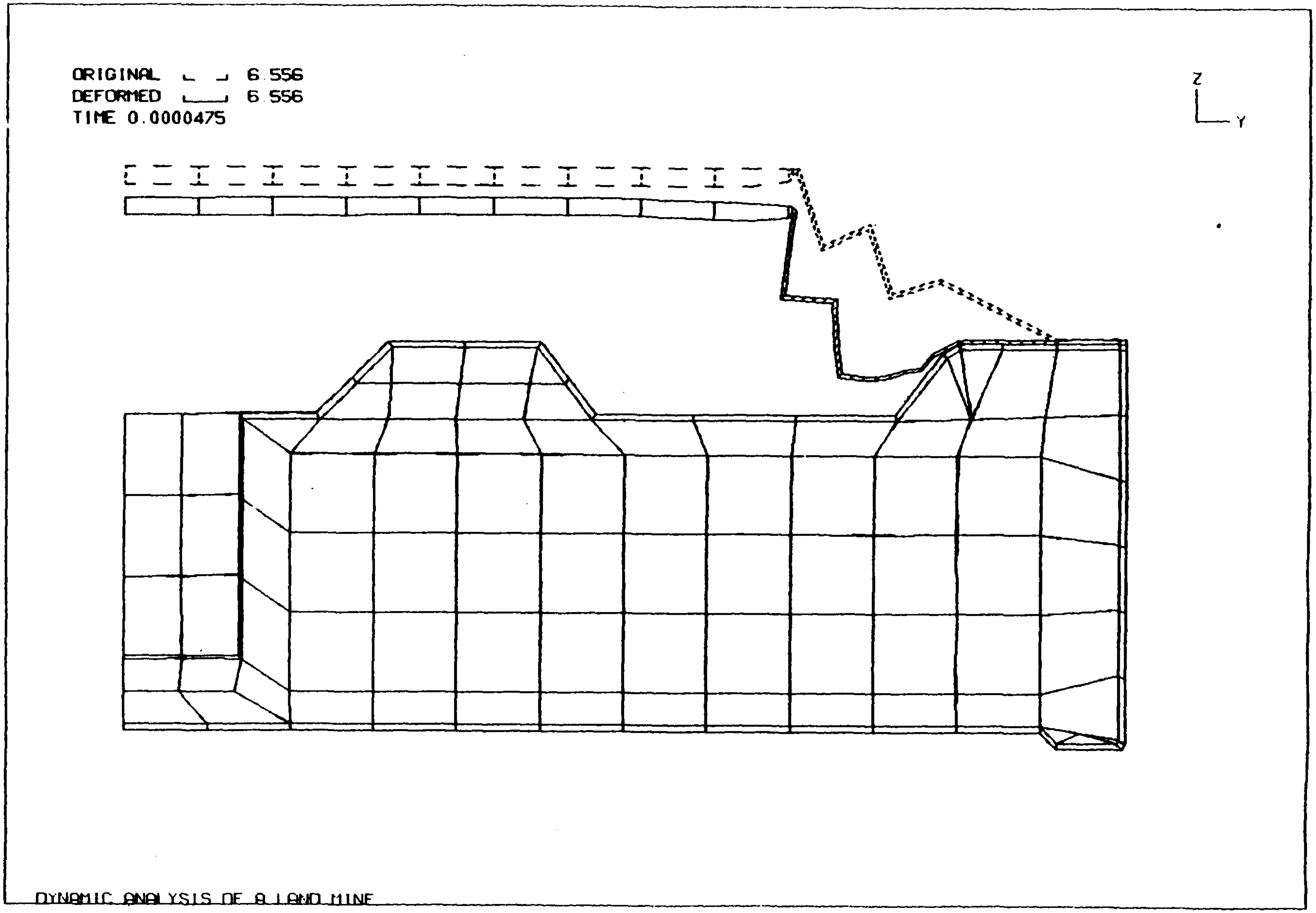


Fig. 17 Deformation of mine at time t = 0.0475 ms

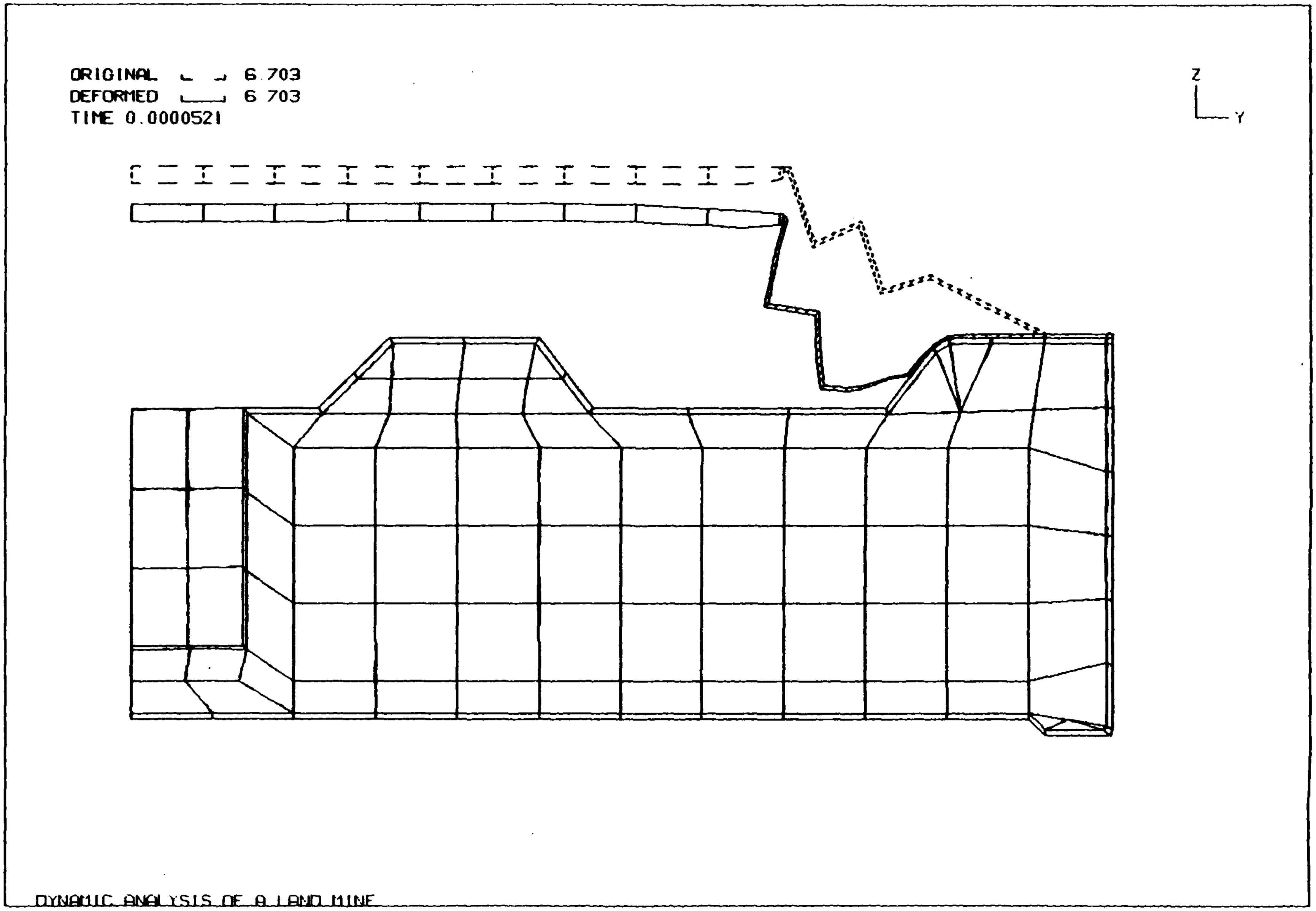


Fig. 18 Deformation of mine at time t = 0.0521 ms

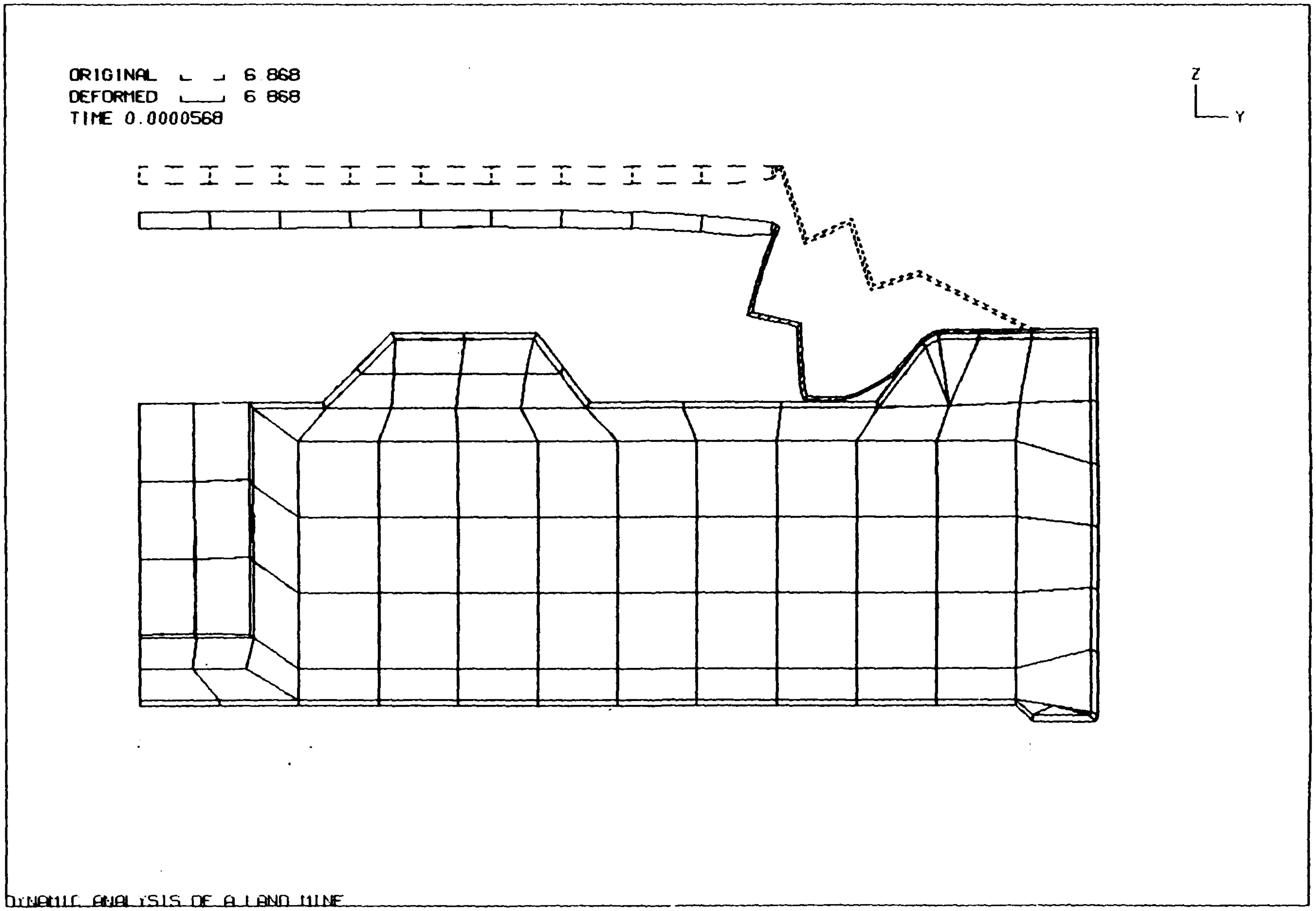


Fig. 19 Deformation of mine at time t = 0.0568 ms

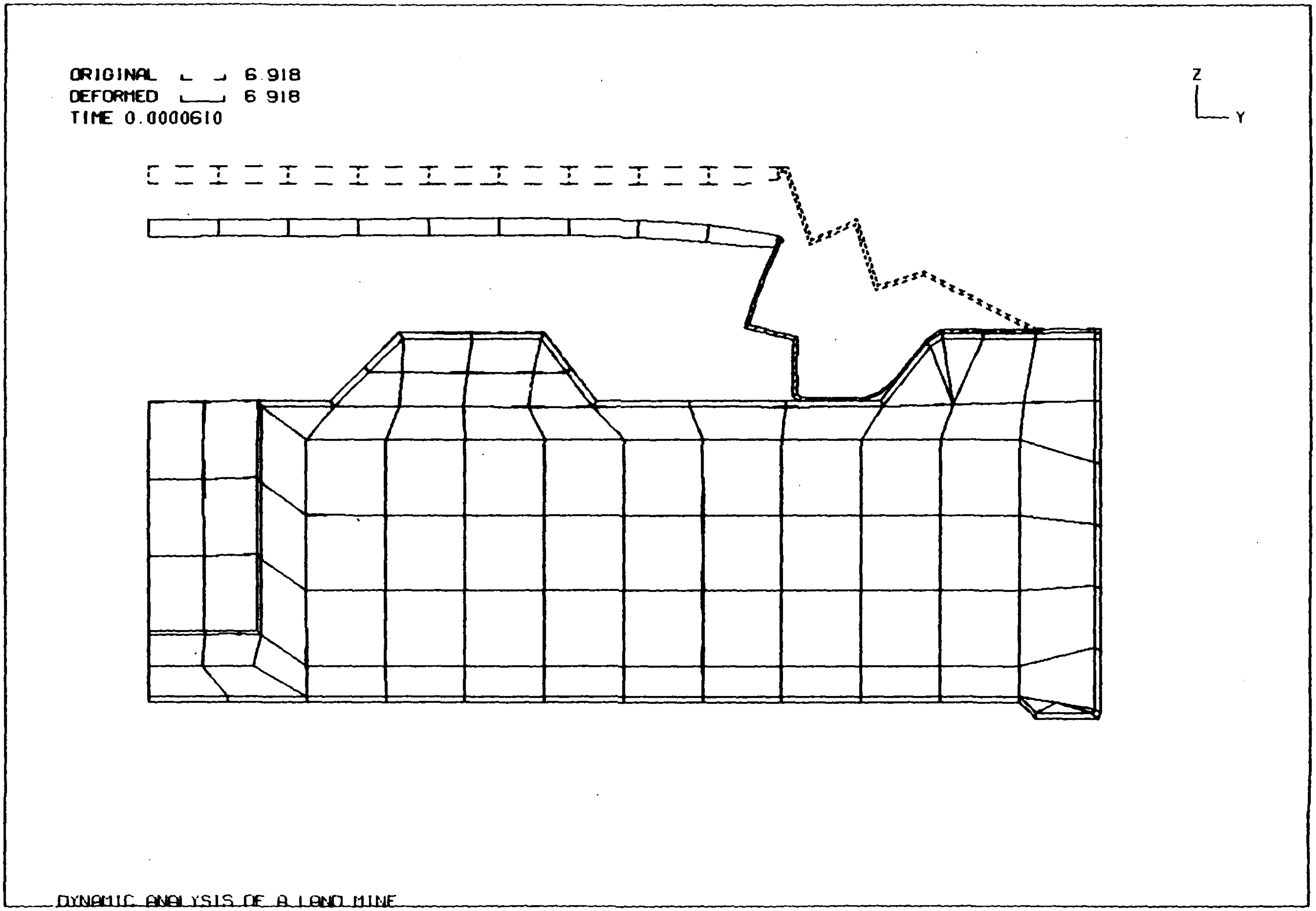


Fig. 20  Deformation of mine at time t = 0.061 ms

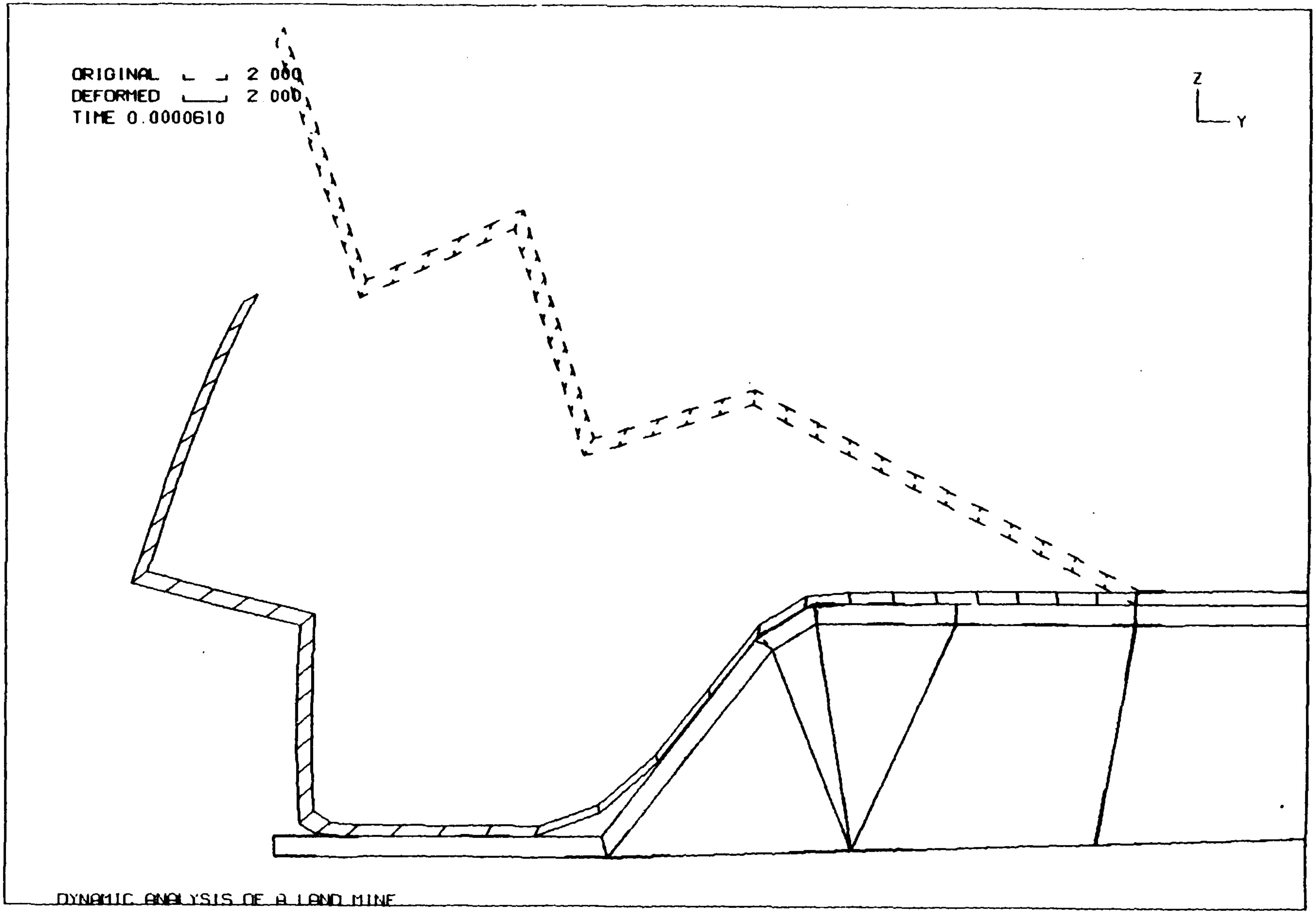


Fig. 21 Large strains in the stepped part of the mine at time t = 0.061 ms

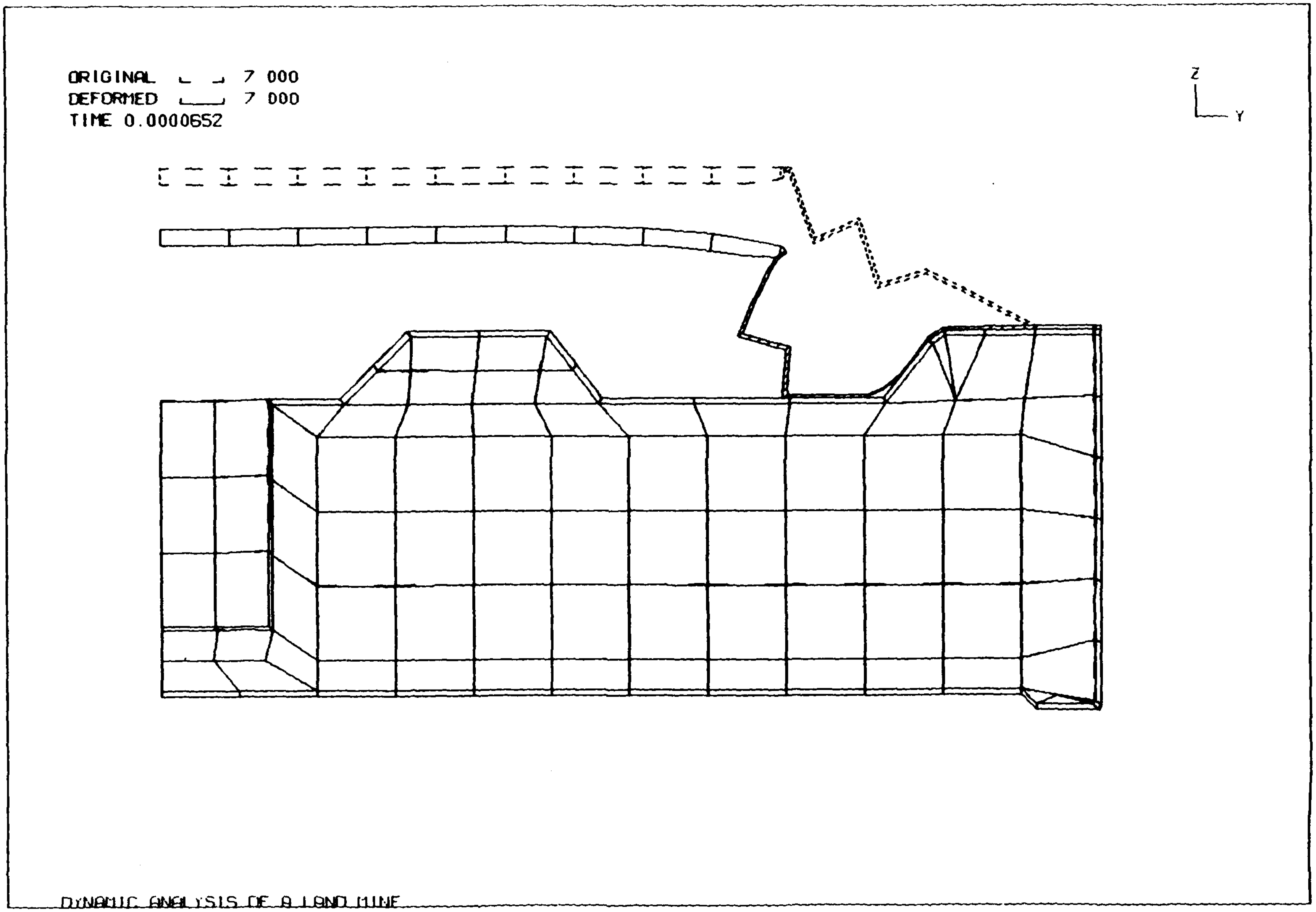


Fig. 22 Deformation of mine at time t = 0.0652 ms

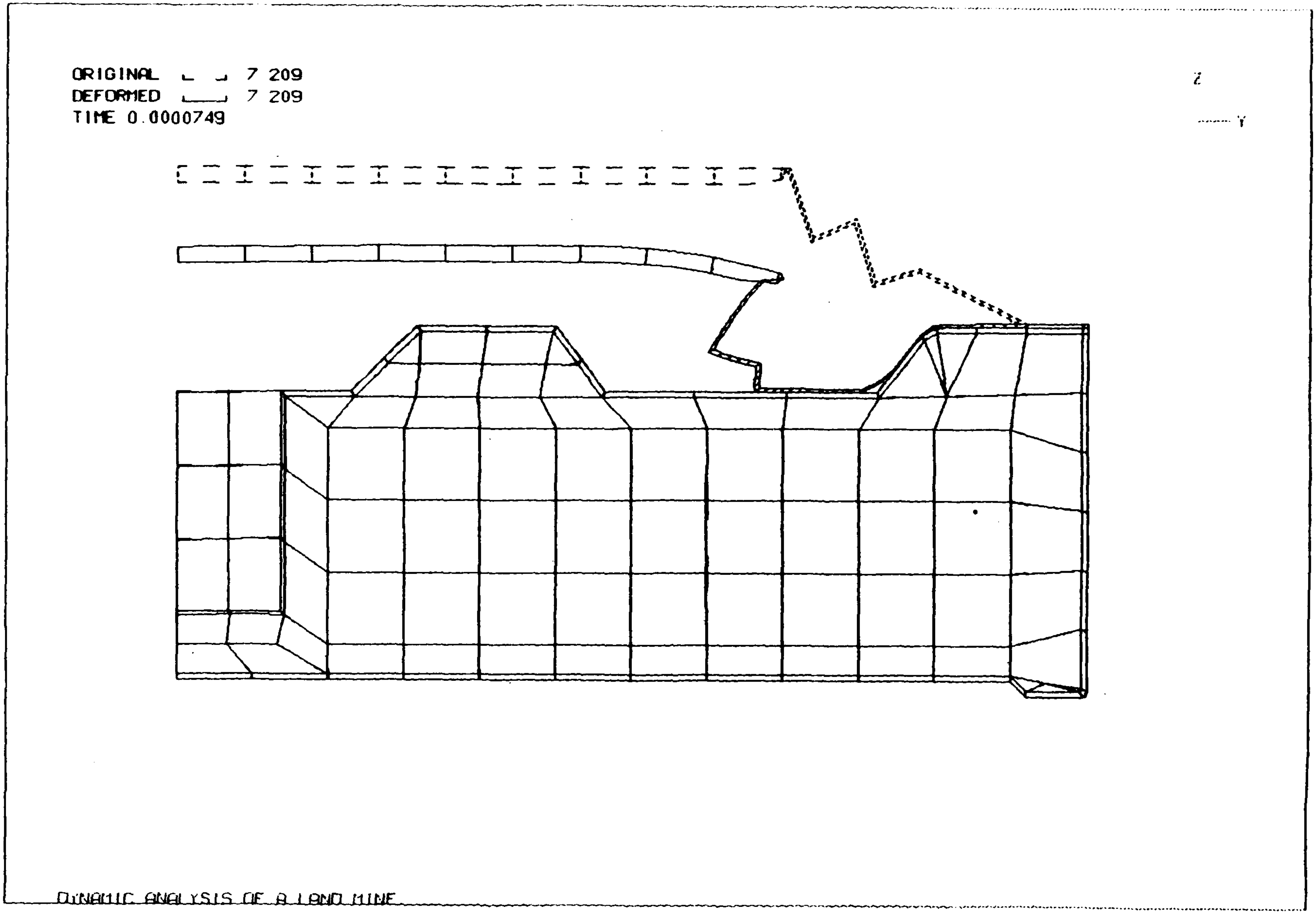


Fig. 23 Deformation of mine at time t = 0.0749 ms

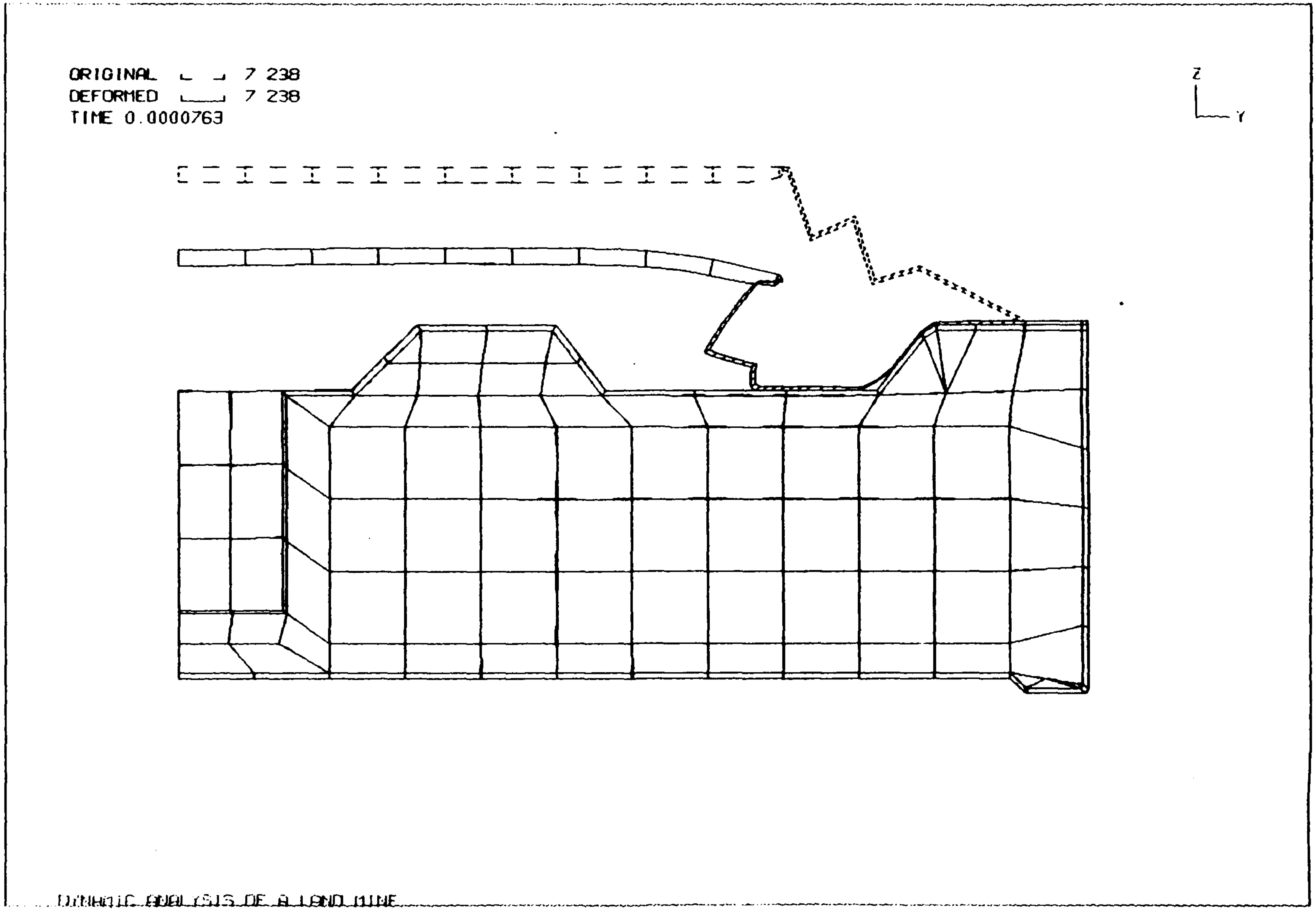


Fig. 24 Deformation of mine at time t = 0.0763 ms

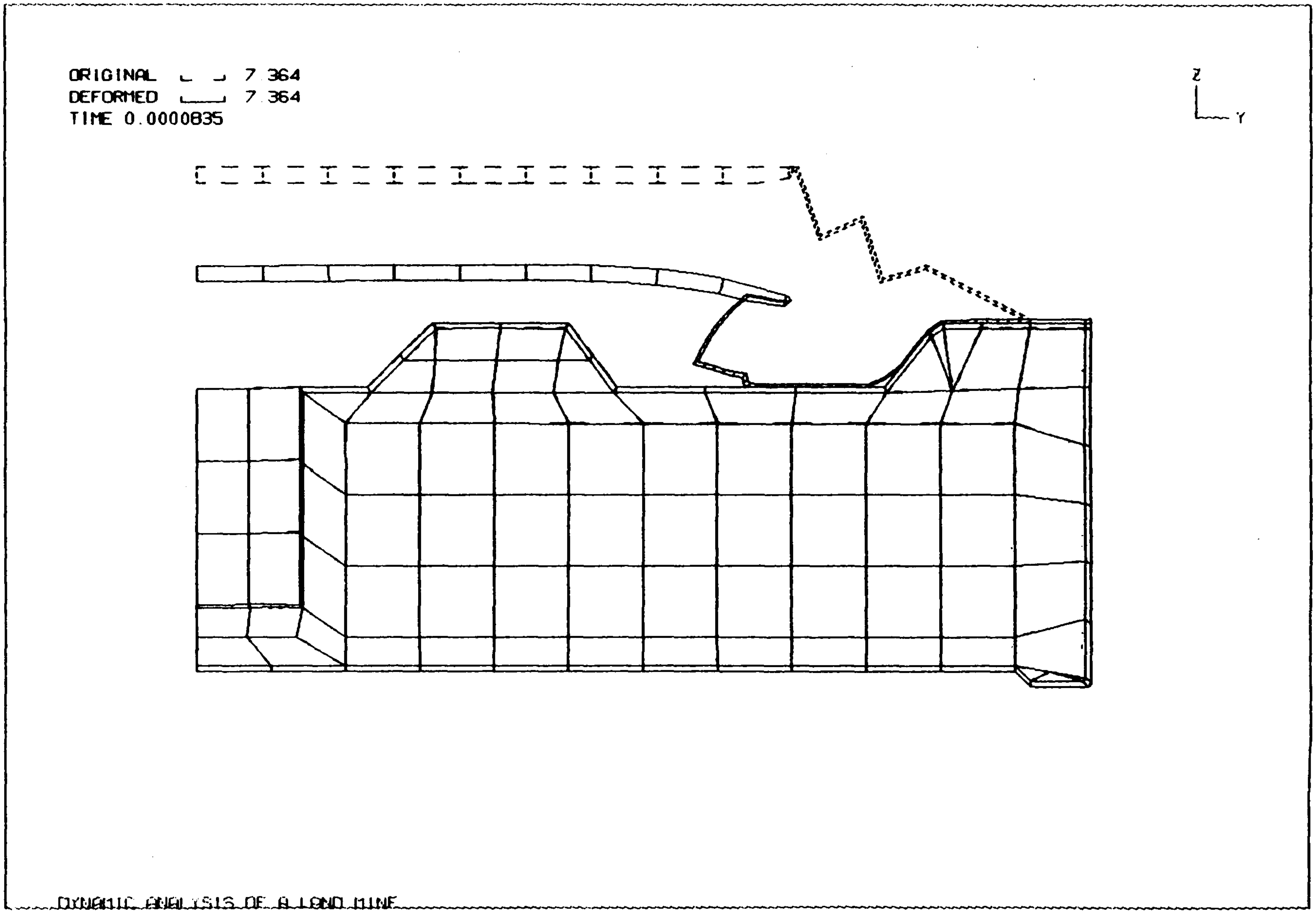


Fig. 25 Deformation of mine at time t = 0.0835 ms

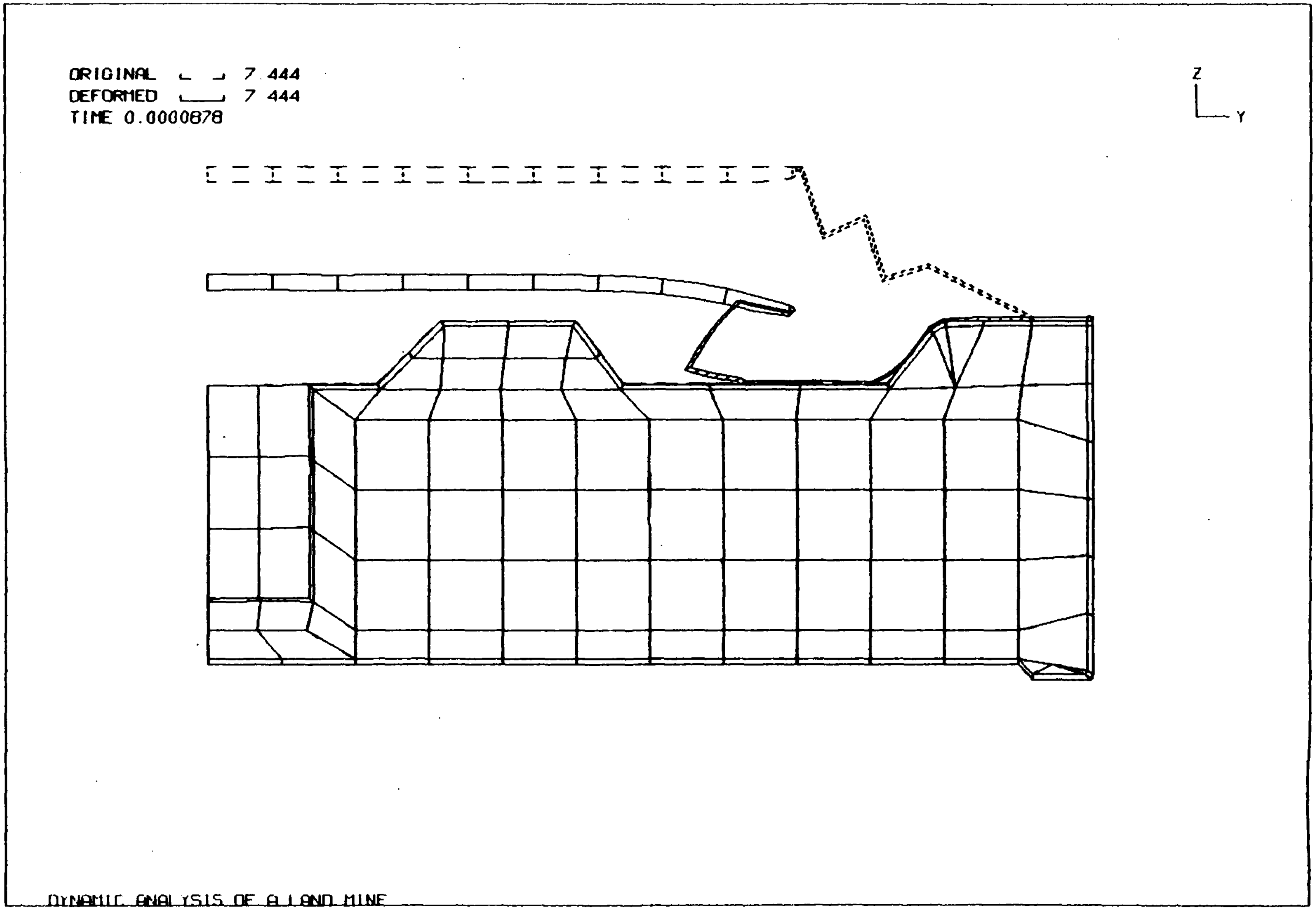


Fig. 26  Deformation of mine at time t = 0.0878 ms

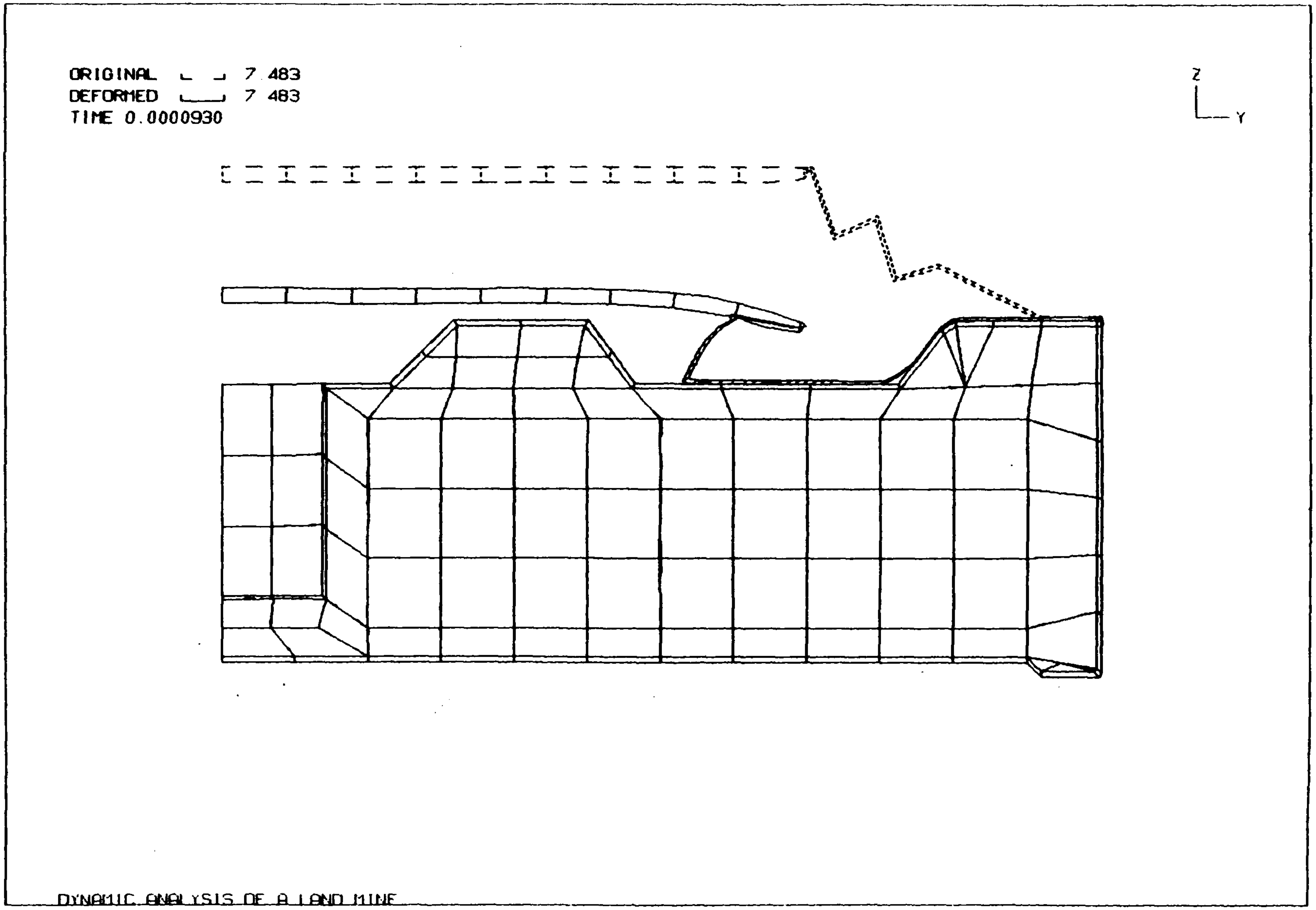


Fig. 27 Deformation of mine at time t = 0.0930 ms

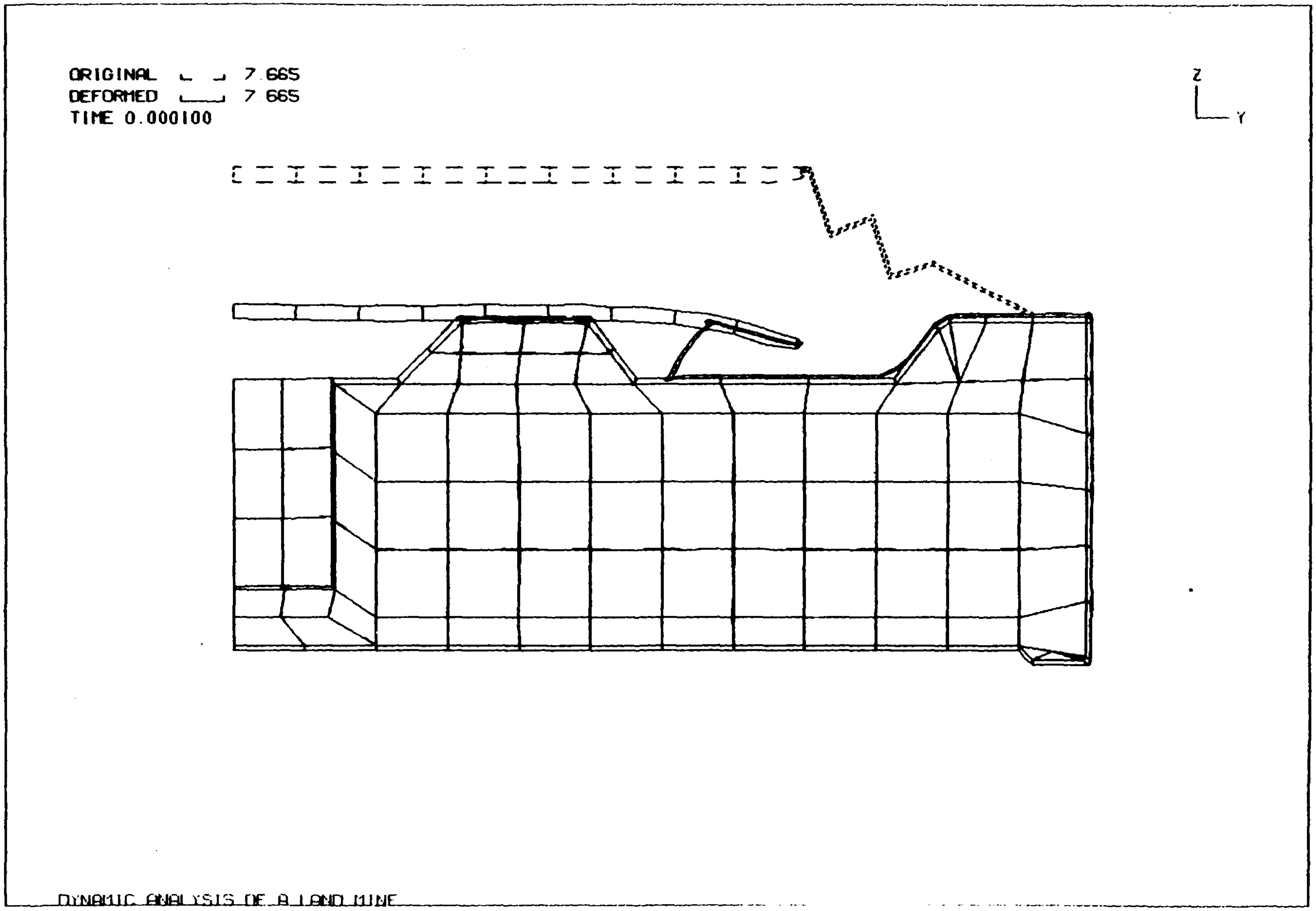


Fig. 28  Deformation of mine at time t = 0.1 ms

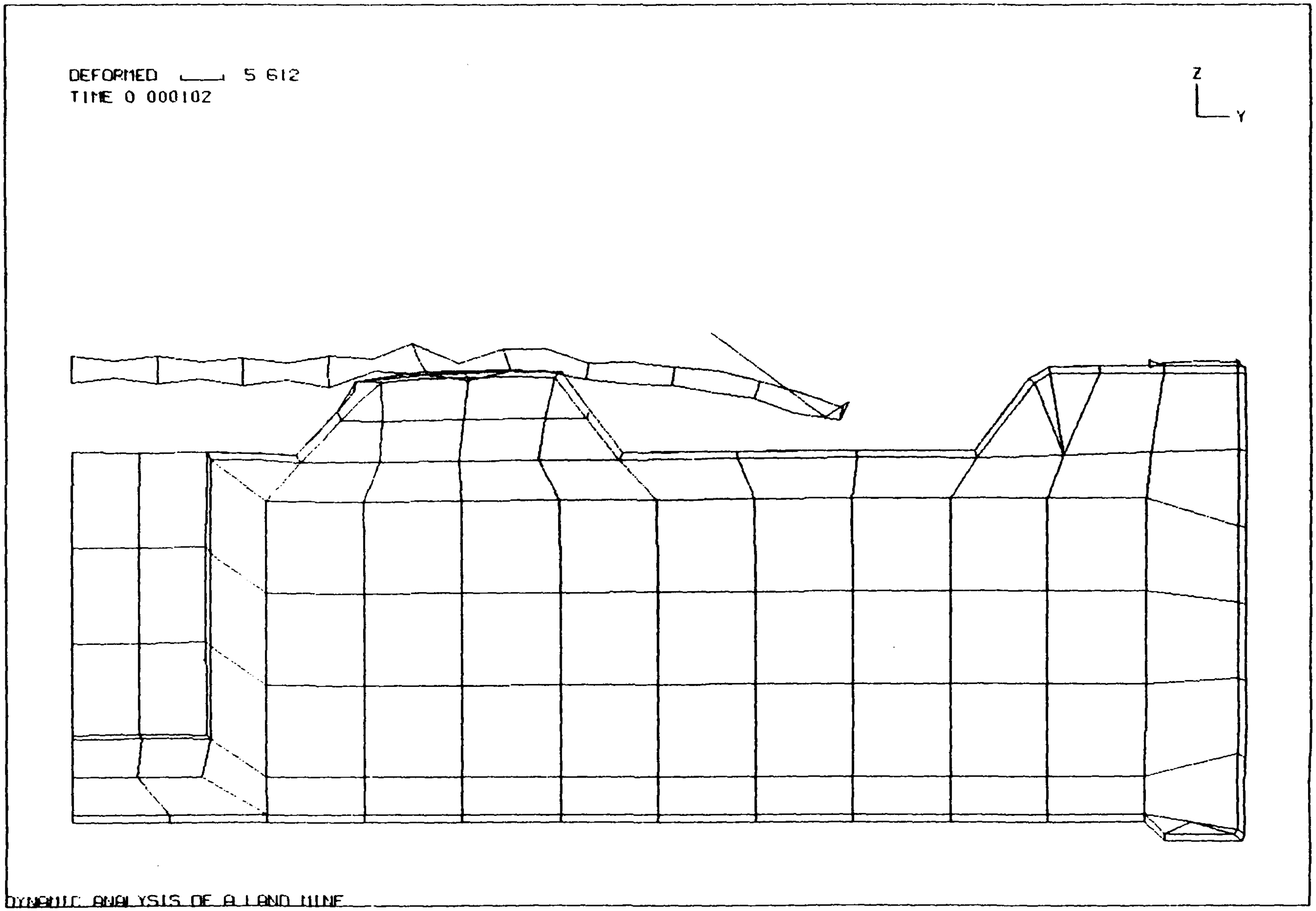


Fig. 29  Damaged top part of the mine at time t = 0.102 ms

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